A Market Mechanism for the Optimal Control of Groundwater and Surface Water Pollution from Nitrates

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Abstract

Nitrate discharges from diffuse agricultural sources have long term effects on groundwater and surface water quality. Market-based instruments have been proposed as a means of balancing the demand for nitrate intensive farming and the capacity of the natural water bodies to dilute nitrates. Trading is complicated by the dispersed, delayed, and protracted effects of diffuse sources. Market mechanisms proposed to date have failed to incorporate these physical characteristics of nitrate pollution correctly.

We propose a new market mechanism for allocating and pricing nitrate discharge permits, based on the design of modern electricity markets which use LP models to find optimal prices and dispatch schedules. The system operates as a centralized auction. The sources submit bids to the auction indicating the benefits gained from each unit of nitrate discharge. The auction operator runs an LP which maximises the benefits from trade, subject to a set of environmental and operational constraints. The LP solution produces the optimal prices and allocations relative to the economic values indicated in the bids.

Our contributions include alternative LP models to suit different hydro-geological and socio-economic conditions. We present a generalized LP model which can include constraints that describe nitrate residence and transport in groundwater and surface water, the ability of water bodies to accept nitrates, and the operational limitations of the commercial sources. We show how to adapt available methods to incorporate the complex physical systems into an optimisation model. We present a double-sided market model which allows the polluters to buy permits, and environmental agents to lease out the ability of the natural water resources to accept nitrates. The model allows the providers of environmental services to participate in the market as sellers.

We build up and prove the concepts by explaining the prices and allocations produced by the LP models. Based on the theory of nodal pricing applied in electricity markets, we discuss the price structures and relationships and show how the prices would reflect the spatial and temporal effects of diffuse nitrate discharges. We interpret the information generated from the outcomes of trading and discuss how the available tools and information can be used by the market participants to optimize their bids. We expand the proposed market model to include point sources, and identify the factors that determine the extent to which the point and nonpoint sources can trade with each other. In addition, we develop measures of the extent to which the diffuse sources themselves can trade with each other. We demonstrate the models and the resulting prices and allocations, using a catchment nitrate transport model.

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List of Abbreviations

BOD	Biochemical Oxygen Demand
DP	Dynamic Program
LP	Linear Program
MILP	Mixed Integer Linear Program
NLP	Non-linear Program
NPS	Nonpoint Source
NZEM	New Zealand Electricity Market
OCED	Organization for Economic Co-operation and Development
OLM	Optimal Loading Model
ORAM	Optimal Resource Allocation Model
PS	Point Source
PS-NPS	Point and Nonpoint Source
RM	Response Matrix
US EPA	US Environmental Protection Authority

Chapter 1

1 INTRODUCTION

1.1 The Tragedy of Global Fresh Water Resources

Water pollution is a tragedy of the commons that both rich and poor nations are striving to mitigate. Many of the world's largest fresh water rivers and aquifers are already contaminated (Jeantheau, 2005). According to United Nation's statistics, twenty percent of the global population lack access to safe drinking water (UNEP, 2008). Each year, 5 to 10 million people die from water related diseases (Jeantheau, 2005). The roots of this hazard lie in the conventional perception of fresh water as a common freely available resource; everyone's resource is treated as no one's resource (Hardin, 1968); and everyone pollutes water for short-sighted economic benefits.

The largest water polluters are commercial entities such as large scale crop and livestock farms and manufacturing plants. The so-called polluters provide products and services, national wealth, employment, and luxurious living, even at the cost of ecosystem health. The world needs factories, farms, cities, and economic development. Neither the economic benefits nor the quality of the environment should be totally forgone for the sake of the other; instead we have to find a compromise.

Fortunately, the self-purification ability of water and the bio-chemical processes of the natural water cycle allow us to load some amount of pollutants into water systems. The question confronted by mankind today is how to distribute this limited pollution intake capacity of water among many competing interests.

1.2 Tradable Permits for Water Pollution

Tradable permit programs have recently appeared as a potential solution to the problem of allocating pollution rights efficiently. The success of air pollution permit trading programs in the West has motivated the idea. Two important factors have contributed to the success of air pollution trading: (1) creation of a tradable standardized commodity which is capable of achieving environmental goals and (2) ability to achieve the environmental goals at least cost by designing the trading program to be as efficient and attractive as possible (Schary & Fisher-Vanden, 2004). However, some sources of water pollution, especially agriculture, have delayed and dispersed effects, making it difficult to identify a standardized commodity which is capable of achieving environmental goals over time and space. From the polluter's view, the right to discharge is the valued commodity, while from the public view, the sustainable pollutant intake capacity of water is the valued commodity. The trading programs should be designed to minimise the cost of trading commodities viewed differently. Therefore, the *market design* has significant effects on the performance of water pollution trading programs; institutional settings and participant behaviour (demand and supply) are also important (Kochtcheeva, 2009).

Though significant effort has been made to design market-based mechanisms for allocating water pollution permits, "much remains to be done in the area of diffuse sources" (O'Shea, 2002). Research to date is mostly dedicated to allocating emission rights to municipal and industrial entities who discharge effluents directly into the rivers (point sources). One reason is that the United States, the country which has pioneered emission permit trading and has the most on-the-ground, active water pollution permit trading programs, does not regulate agricultural discharges, and thus the trading programs are usually focused on point sources ignoring the diffuse agricultural sources.

The effects of diffuse (nonpoint) sources spread widely over time and space, so the management of diffuse sources requires an integration of physical and economic models. Recent attempts to develop market-based instruments are based on simplifications of the physical systems (US EPA 2007; NIWA 2009), rather than integration. The ability of such systems to achieve environmental goals over time and space cannot be guaranteed.

1.3 Scope of the Work and Contributions

This thesis is about the design of a trading program (a market mechanism) for allocating water pollution permits. We focus specifically on designing a market for trading *nitrate* discharge permits in agricultural watersheds, with particular concern on diffuse agricultural sources but considering all types of pollutant sources. We choose nitrate in particular because it is a critical agricultural water pollutant which affects both groundwater and surface water, and the way nitrate pollution works is complex compared to the other pollutants. However, we develop the models and the concepts so that they are adoptable and applicable to other water pollutants as well as other environmental problems.

The first stage of the work is identifying the characteristics of the problem: the issues related to trading nitrate discharge permits which arise from the hydro-geology of the watershed, characteristics of different types of polluters, and environmental goals.

The second stage is designing a trading program to be able to addresses all those issues. In the market design process, we study how to define the permits, what serves as the basis for trading; how to deal with the spatial and temporal complexity in nitrate transport via groundwater; how to set the time frames for trading; how the trading system should interface with different users; how the required information is obtained, processed, and shared; and, how the market is operated.

The proposed trading framework is based on the architecture of modern electricity markets which use LP models to find the optimal prices and allocations, but we have incorporated features of successful emission and water pollution trading programs.

Since the market design is based on optimisation models, the next stage of the work is about developing LP models for the market. We study the physical and economic constraints which drive the prices and allocations, include them in the LP models, and discuss their effects on prices and allocations.

A considerable portion of this thesis is dedicated to interpreting and explaining the prices and allocations produced by the LP models. Based on the theory of nodal pricing applied in electricity markets, we discuss the price structures and relationships. We show how the prices would reflect the spatial and temporal effects of diffuse nitrate discharges. We interpret the important information generated from the outcomes of trading, for example, the economic values of investment in treatment and remediation projects to remove nitrates from water bodies.

We present various design options and extensions and their consequences on prices and allocations. We discuss favourable institutional, behavioural, and natural settings for the proposed trading system, and how to adopt the market design and the models to facilitate trade under various conditions.

The key contributions of this thesis are summarized below.

1. Identification of hydro-geological factors that should be considered in trading nitrate discharge permits, mainly time lags, attenuation, and protracted delivery profiles associated with nitrate transport in groundwater. Also, the additional difficulties that arise from the presence of multiple receptors and point and nonpoint sources together are recognized.

2. Adaptation of the “response matrix technique” to be used in a tradable permit program as a proxy for an integrated physical model to describe the groundwater solute transport system.

3. Guidelines for selecting the spatial and temporal measures of water quality, as the basis for a trading program. We discuss how to select the planning horizon, the time intervals at which the water quality constraints should be imposed, and other time-related parameters, based on the available hydro-geological information, to meet the requirements of a market mechanism. We also discuss the issues arising from the choice of type, location, and number of receptors; and how to choose a compromise.

4. A basic LP which models the essentials of a market in nitrite discharge permits among nonpoint sources. The basic model includes the effects of nitrate

transport in groundwater using the response matrix technique. Permit allocations are constrained by the ability of the receptors to accept and dilute nitrates, and the bids submitted by the participants.

5. A generalized LP model which can include all types of generally applicable physical and economic constraints. The generalized model allows constraints that describe nitrate residence and transport in surface water, together with the response matrix which describes nitrate transport in groundwater. The model can include other physical limitations in the water system as well as demand-side (private) restrictions.
6. A double-sided market model which allows the polluters to buy permits, and the environmental (or public) agents to sell (or lease out) the ability of the natural water resources to accept and dilute nitrates. The model allows third parties, such as providers of environmental services who have the ability to remove nitrates from water bodies, to participate in the market as sellers.
7. Information for the market participants to optimize their behaviour in the market. The participant-side optimisation is beyond the scope of this thesis; we discuss how the market participants can use available information to optimise their bids and offers.
8. Expansion of the market models to include point sources and identification of the factors that determine the extent to which the two types of pollution sources can interact in the market.
9. Measures of the ability of the nonpoint sources to trade with each other.
10. Ideas for expanding the market models to include the effects of surface runoff, profit function discontinuities (integer constraints), and compliance-related penalties and rewards; setting initial permit allocations; and applying the models and concepts to other environmental problems.

Additionally, we provide numerical demonstrations of the models and their outcomes using a small case study.

1.4 Thesis Outline

The rest of this thesis is structured as follows.

Chapter 2 is about water pollution from nitrates. We discuss the ways by which nitrates migrate to groundwater and surface water, and the consequences of having nitrate in water. We summarise the available tools and techniques to measure and control water pollution from nitrates.

Chapter 3 presents the non-market based approaches to the optimal control of water pollution. We discuss the literature on integrated simulation and optimisation based approaches to the optimal control of nitrate pollution from nonpoint sources. Both convex and non-convex optimisation models are discussed.

Chapter 4 covers the main body of literature relevant for this work, about state-of-the-art water pollution permit trading systems.

Chapter 5 is about the physical characteristics of the problem addressed in this thesis. Having understood the way nitrate pollution works, we discuss the basic requirements of a market-based approach for allocating nitrate discharge permits. We analyse the applicability of the available systems discussed in Chapter 4 and highlight the difficulties of using them for nitrates and nonpoint sources. In addition, we analyse the market designs for other resources such as electricity which have similar complexity, and highlight the applicability for pollution permit trading, especially for nitrates and nonpoint sources.

Chapter 6 proposes a new market mechanism for allocating nitrate discharge permits among nonpoint sources. The market is designed to use an LP to find the optimal prices and allocations ex-ante.

Chapter 7 presents the basic and generalised LP models discussed under the thesis contributions 5 and 6 above. Different types of applicable constraints are also discussed. This chapter includes interpretations and explanations of the prices and allocations generated by the LP models, price structures and relationships, gains from trade, and issues related to settlement.

Chapter 8 presents the double sided market discussed under thesis contribution 7 above. We present another LP model for this market which facilitates the pollution sources and environmental agents to trade different commodities in a combined market.

Chapter 9 is for the market participants, mainly the agricultural sources and the environmental authorities who participate in the market as environmental agents. We do not present any participant-side optimisation model, but we discuss the information that would be useful for the participants to optimise their decisions.

Chapter 10 presents numerical demonstrations of the results (prices and allocations) generated from the models discussed in Chapters 7 and 8. This chapter covers the ways of dealing with initial (pre-trade) permit holdings also.

Chapter 11 is about extending the market to include point sources, opportunities for trade between point and nonpoint sources, and the ability of the nonpoint sources themselves to trade with each other. This chapter highlights the physical and economic conditions under which the point and nonpoint sources can interact in the market. In addition we discuss some measures of the extent to which major players in the market (nonpoint sources) can trade with each other.

Chapter 12 wraps up the thesis, discussing possible extensions and applications of the models and concepts, our conclusions, and directions for further research.

Chapter 2

2 WATER POLLUTION AND NITRATES

2.1 Introduction

This thesis focuses on water pollution from nitrates. This chapter discusses the background of the problem addressed in this thesis. First, we discuss general concerns about water pollution, and then provide an introduction to nutrients pollution. We discuss nitrate pollution, being particularly concerned with nitrate transport in groundwater, a process which worsens nitrate pollution. We provide a brief overview of the general solute transport equation which is used to model nitrate transport in groundwater. Then we outline the essential concerns for the control of nitrate pollution. The chapter closes with a description of alternative pollution control policies applicable for nitrates.

2.2 General Background: Water Pollution

2.2.1 Water Pollution and Water Pollutants

Water pollution is any undesirable change in the physical, chemical, or biological characteristics of water that can harmfully affect the health, survival, or activities of human or other living organisms (PCE, 2010). The most common water pollutants are nutrients, organic matter, heavy metals, microbial contaminants, toxic organic compounds (oil, pesticides, some plastics, industrial chemicals), salts, acids, sediment, suspended particles, and high temperature (Revenga & Mock, 2001).

Pollutants affect water quality in different ways. Usually water pollutants are not uniformly mixed in water whereas some air pollutants such as CO_2 and GHG are considered to be uniformly mixed in the medium (Keudel, 2006). If a pollutant is uniformly mixed, the effects of discharge at any time at any location are the same, but with non-uniformly mixed pollutants, both the time and location of discharge matter. Some pollutants such as heavy metals and plastic wastes are accumulated in water bodies. In contrast, pollutants such as nutrients and salt are assimilative rather than accumulative, but the assimilative capacities of the water bodies are limited, beyond the limit they may be accumulated. This work is about a non-uniformly mixed assimilative water pollutant, nitrate.

2.2.2 Groundwater and Surface Water Pollution

Natural water that exists as groundwater or surface water is often contaminated by human activities. Streams and lakes are polluted mainly by municipal and industrial discharges, storm water runoff, and contaminated groundwater inflows. Groundwater pollution occurs from disposal or dissemination of pollutants on the land surface or into the soil, because these pollutants (for example, agricultural chemicals) contaminate the percolating waters that recharge the groundwater aquifers. In extreme circumstances, for example, in flood conditions, contaminated surface water may flow into groundwater aquifers.

Surface water pollution is readily visible as a change of colour, smell, or appearance; growth of weeds; and extinction of aquatic species. Groundwater pollution, by contrast, remains invisible for a long time because groundwater flows slowly and does not flow towards a single outlet (Harter, 2003). As a consequence, groundwater pollution has delayed and dispersed effects. Natural cleanup of groundwater takes many years unless expensive treatments are carried out. As drinking water mostly comes from groundwater, significant effort has been made to prevent long terms hazards caused by groundwater pollution. In recent years, the US Department of Agriculture has spent \$3.5 billion per year on conservation programs to reduce agricultural discharges, the number one source of groundwater pollution (Faeth, 2000). Surface water pollution, worsened by groundwater pollution, still remains a global hazard. Every year, about 2 million people, mostly children under five years, die from diseases caused by surface water pollution (UNEP, 2008).

2.2.3 Point Sources and Nonpoint Sources

Water pollution occurs from two types of sources, point sources and nonpoint sources. Sources that discharge effluents directly into water bodies through pipes, drains, or canals are called “point sources”. Processing and manufacturing plants, sewage treatment works, and urban waste water systems usually discharge effluents directly into waterways, and therefore they are point sources. Point sources have a single point of origin and are introduced into a receiving surface water body from a specific outlet. In contrast, “nonpoint sources” are diffuse, they originate in a wider area, and hence they do not have a single point of origin. Seepage and runoff of agricultural fertilizer, pesticides, and animal wastes from agricultural land are the major nonpoint source contributors of water pollution. Other nonpoint sources are urban and suburban storm water, mining, construction, and forestry.

Damage from point and nonpoint sources occurs differently. Point sources instantly pollute surface water while nonpoint sources pollute both groundwater and surface water slowly over a long period.

2.2.4 Traditional and Modern Sources of Pollution

About a century ago, the major causes of water pollution were untreated human wastes and factory effluents (Ongley, 1996; Revenga & Mock, 2001). Today, developed countries have managed to reduce the adverse effects of these point sources through treatment and disposal technologies and pollution laws, whereas many developing countries are still struggling with the conventional water pollution sources such as sewage and industrial effluents (Revenga & Mock, 2001). Still, the developed countries are suffering from rising nonpoint source pollution caused by agriculture, storm water runoff, mining, construction, and other development activities. For many developed countries in North America and Europe, intensive agriculture is the single greatest threat to their precious water resources (OCED, 2008;

Ongley, 1996; Revenga & Mock, 2001; Ribaudo, Horan, & Smith., 1999; USGS, 1999).

2.2.5 Agricultural Pollution

Global agriculture, which includes crops, livestock, aquaculture, and forestry, is the main source of the world's food supply (UNESCO, 2003), but an emerging threat to fresh water resources. Agricultural fertilizers, pesticides, manure, and livestock effluents are significant causes of water pollution. Agricultural pollutants include nutrients (mainly nitrogen and phosphorus), sediment, pesticides, salts, and pathogens (Ribaudo, et al., 1999). The cause of high nutrient concentrations in most rivers and aquifers is the "increased use of manure and manufactured fertilizer in global agriculture" (Revenga & Mock, 2001). The US EPA has declared agriculture to be the "leading source of impairment in the nation's rivers and lakes" (Ongley, 1996). Rising nutrients pollution in Canada, Australia, New Zealand, Hungary, Portugal, Spain and many other countries is related to the expansion of agricultural production (OCED, 2008). In New Zealand, some rivers flowing across pastoral land fail to meet environmental guidelines, while shallow groundwater aquifers in dairying catchments are under threat (OCED, 2008).

2.3 Nutrient Pollution

2.3.1 Nutrients in Water

Nutrients are chemical elements and combinations of elements that all living beings need to grow and survive (Mueller & Helsel, 1996). Water systems need nutrients, but excess nutrients in water bodies cause serious problems. The most commonly found nutrients in water are nitrogen and phosphorus. In water bodies, they are found in various forms such as nitrate, nitrite, ammonia, organic nitrogen (in the form of plant material or other organic compounds), and phosphates (orthophosphate and others). Nitrate is the most widespread form of nitrogen, and phosphate is the most widespread form of phosphorus found in natural water bodies (Mueller & Helsel, 1996).

2.3.2 Surface Water Pollution from Nutrients

The major sources of nutrients in surface water are sewage treatment facilities, soil erosion and runoff from agricultural land, and contaminated groundwater inflows. Surface water may contain all types of nutrients, including nitrate, phosphate, and ammonia.

Nutrients in surface water stimulate plant growth (algae and other weeds). The process of nutrient enrichment in water bodies causing plant growth is called “eutrophication.” Intensive growth of algae and other weeds in surface waters prevents sunlight infiltrating deep waters, reduces the dissolved oxygen level in water, and disturbs the natural habitat. Once these algae die, the decomposition process consumes available oxygen and creates a shortage of oxygen in the ecosystem, threatening the lives of fish and other aquatic species (Wiederholt & Johnson, 2005). The shortage of oxygen in water is called “hypoxia.” Excess nutrients in surface waters have other adverse effects such as clogged pipelines and reduced recreational opportunities (Ribaudo, et al., 1999).

2.3.3 Groundwater Pollution from Nutrients

Nitrate is the most widespread nutrient in groundwater. Agriculture and septic systems are the major causes. Section 2.4 provides more discussion on how and why nitrate migrates to groundwater, and the consequences of groundwater pollution from nitrates.

2.3.4 Ocean Pollution from Nutrients

The consequences of nutrient discharge into water do not end in the receiving water bodies, but continue towards the oceans. Nutrients carried down to the oceans via rivers cause ocean dead zones. The Gulf of Mexico dead zone is steadily extending due to nutrient pollution in US rivers (Alexander et al., 2008). The Mississippi River alone carries about 0.95 million metric tonnes of nitrate pollution into the Gulf annually (USGS, 2000).

2.4 Nitrate Pollution

2.4.1 Significance and Global Intensity

High nitrate concentration in water is a major (perhaps the most severe) water pollution problem. Most of the rivers in Europe have "nitrate levels four times the norms found in nature" (Lenntech Water Treatment & Air Purification Holding B.V., 2006). Although nitrate pollution tends to be severe in Europe and North America, the threat is global, and high nitrate concentrations are recorded in China and South Africa also (Revenga & Mock, 2001; Staff of World Resources Program, 1998). In New Zealand's Waikato region, groundwater nitrate levels commonly exceed the national drinking water standards owing to intensive market gardening and livestock farming (Wright, 2007). Surplus nitrates in water harm the aquatic ecosystems as explained above, and high nitrate concentration in drinking water can cause illness. In particular, excess nitrates in drinking water can cause "blue baby" syndrome in infants (Wiederholt & Johnson, 2005). Chronic exposure to high nitrate levels cause diuresis, increased starchy deposits, and haemorrhage of the spleen (US EPA, 2006).

2.4.2 How Does Nitrate Migrate to Groundwater and Surface Water?

Nitrate migration to fresh water is mainly a consequence of nitrogen overload on the land surface. Nitrogen (N) is an essential nutrient for all living organisms and is abundant in the atmosphere as nitrogen gas (N_2), but the plants cannot take up atmospheric nitrogen gas. Plants can take up nitrogen in two solid forms: ammonium (NH_4^+) and nitrate (No_3^-). Plants consume nitrate and ammonium from the soil and animals obtain nitrogen by consuming living or dead organic matter that contains nitrogen.

Intensive application of nitrogen fertilizer and manure on agricultural land improves crop harvest. Nitrogen fertilizer products include ammonia (NH_3), ammonium nitrate (NH_4NO_3), ammonium sulphate ($[NH_4]_2SO_2$), and urea. Organic nitrogen is found in manure, sewage waste, compost, decaying leaves and trees, and dead animal parts. In the soil, nitrogen contained in organic matter is converted into ammonia, and then to ammonium, by some soil organisms. Ammonium is converted into nitrate through a process called "nitrification." Nitrate in the soil may be taken up by plants, subjected to de-nitrification[1], carried down to surface water bodies by surface or sub-surface runoff, or leach into the groundwater aquifer. This process is explained by the "nitrogen cycle" shown in Figure 2.1 below.

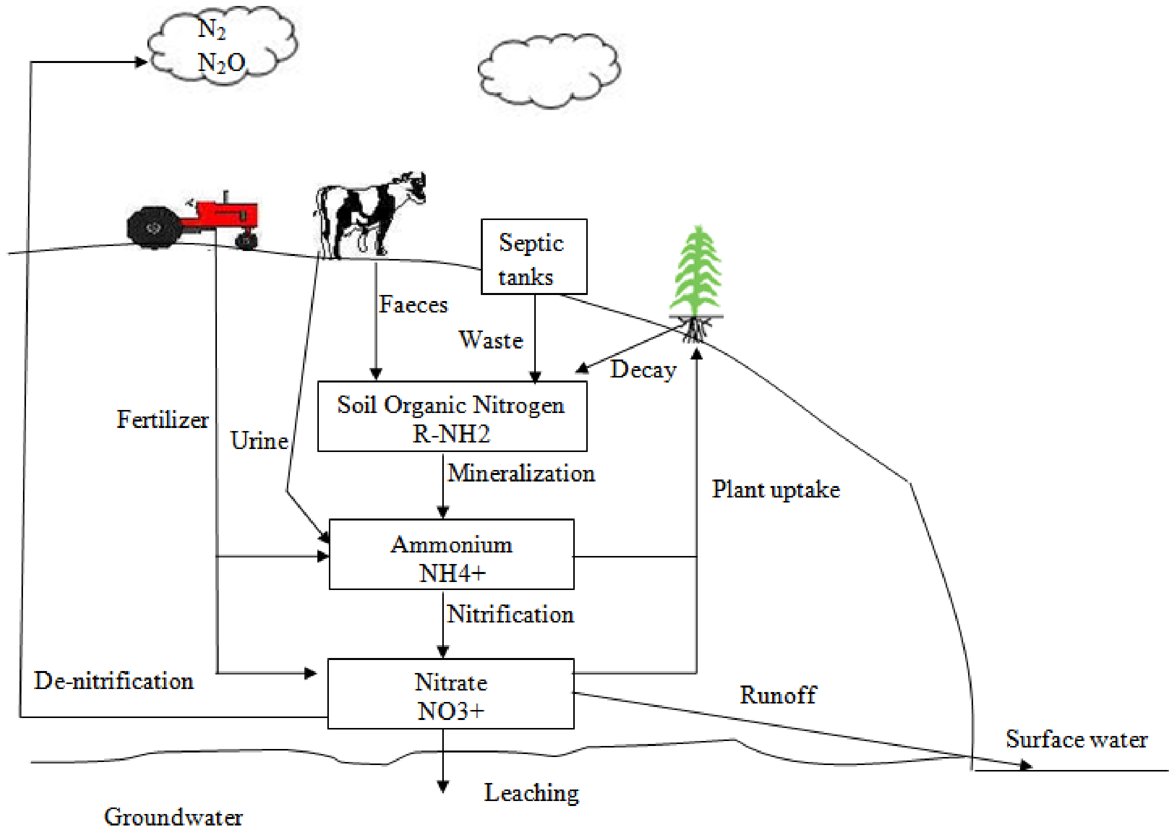

Figure 2.1: Nitrogen Cycle.

In agricultural catchments, due to intensive fertilizer usage and deposition of organic wastes, soil nitrate content usually exceeds plant demand and the de-nitrification

[1] De-nitrification is a process which converts nitrate into nitrogen gas (Conan, Bouraoui, Turpin, Marsily, & Bidoglio, 2003; Deutsch, Gruber, Key, & Sarmiento, 2001; Korom, 1992). Nitrate and the intermediate products of the de-nitrification process (nitrite and nitric oxide) serve as electron accepters for the oxidization of organic and inorganic compounds. Usually de-nitrification is high in anaerobic (low oxygen concentration) conditions (Deutsch, et al., 2001). Availability of organic matter and other chemical compounds which provide electrons from oxidation (for example, pyrite FeS_2) stimulate de-nitrification. De-nitrification may take place in soils, groundwater, surface water, wetlands, and oceans depending on the availability of favourable conditions.

capacity of the soil. The surplus nitrate is lost to the environment via runoff or leaching, mainly due to the high solubility of nitrate. However, soil nitrate has a greater potential to leach down to groundwater aquifers than to be carried down by surface runoff (Czapar, Laflen, McIsaac, & McKenna, 2005). In groundwater, nitrate moves at approximately the same rate as water, and often ends up in surface water through groundwater flux. Nitrate is quite persistent in water, and likely to remain in water until consumed by some plants or taken away by some external process (US EPA, 2006).

Apart from groundwater discharge, surface water bodies such as streams and lakes receive nitrates from municipal and industrial point sources. Sewage treatment plants are the major point sources of nitrates.

2.4.3 Soil Nitrogen Balance and Estimating Nitrate Loading

The amount of nitrate leaching (loading) from soil to groundwater is usually estimated from the soil nitrogen balance equation. The soil nitrogen balance measures the difference between the total nitrogen input (mainly from fertilisers and livestock manure), and the sum of plant uptake (mainly crops and forage) and nitrogen loss due to de-nitrification (OCED, 2001). A surplus means potential environmental pollution, because the surplus is most likely to leach into the groundwater system as nitrate.

Precise estimates of nitrate leaching to groundwater and loss due to surface or subsurface runoff can be obtained from a detailed simulation of the nitrogen cycle (Neitsch, Arnold, Kiniry, & Williams, 2005; Pohlert, Huisman, Breuer, & Frede, 2007). The amount of nitrate leaching from soil to groundwater depends on regional climate, geography, soil properties, type of crop, type of livestock, and farm management practices. Many computer programs are available to simulate the nitrogen cycle and calculate the nitrate leaching, given the above parameters as inputs. SWAT (Neitsch, et al., 2005) and GLEAMS (Knisel, 1993) are some commonly used soil models which have the capability to estimate the nitrate leaching. OVERSEER is a computer based nutrient budget program used in New Zealand to estimate the nitrogen loss to the environment from agricultural land uses. The amount of nitrogen lost from land use is usually considered as the amount that leaches into the underlying aquifer, assuming that the amount of nitrogen carried away by surface and subsurface runoff is negligible.

2.4.4 Nitrate Fate in Groundwater and Surface Water

Nitrates discharged into surface water may be taken up by aquatic plants and species, subjected to de-nitrification, or carried down towards the oceans. Oxygen depletion and availability of organic matter may stimulate surface water de-nitrification.

The fate of leached nitrates in groundwater is determined by complex hydro-geological processes described by groundwater science. Nitrate may flow with groundwater (advection), disperse away from groundwater flow directions (dispersion), or transform into other chemical forms (chemical reaction).

Because groundwater flow is relatively slow compared to surface water, nitrate may travel with groundwater for many decades until being discharged into a surface water body. As groundwater does not usually travel towards a single outlet, nitrate leached from the same location may end in different outlets over different time scales. Therefore, nitrate pollution is strongly related to nitrate transport in groundwater.

2.5 Nitrate Transport in Groundwater

2.5.1 Scientific Background

The foundation for the science of solute transport in groundwater was Darcy’s (1856) experimental results on groundwater flow in a porous medium (Zheng & Bennett, 2002). The efforts of Darcy and many of his followers resulted in the development of mathematical formulations which describe solute transport in groundwater. These general formulations are used to model nitrate transport in groundwater and to estimate the nitrate concentration across space and time caused by spatially distributed and temporally variable sources.

2.5.2 Groundwater Solute Transport Equation

The partial differential equation which describes the fate and transport of a contaminant in a three-dimensional transient groundwater flow system is given below (Zheng & Bennett, 2002).

$$\frac{\partial(\theta C)}{\partial t} = \frac{\partial}{\partial x}\left(\theta D_{xx}\frac{\partial C}{\partial x} + \theta D_{xy}\frac{\partial C}{\partial y} + \theta D_{xz}\frac{\partial C}{\partial z}\right) + \frac{\partial}{\partial y}\left(\theta D_{yx}\frac{\partial C}{\partial x} + \theta D_{yy}\frac{\partial C}{\partial y} + \theta D_{yz}\frac{\partial C}{\partial z}\right) +$$
$$\frac{\partial}{\partial z}\left(\theta D_{zx}\frac{\partial C}{\partial x} + \theta D_{zy}\frac{\partial C}{\partial y} + \theta D_{zz}\frac{\partial C}{\partial z}\right) + \frac{\partial(q_x C)}{\partial x} + \frac{\partial(q_y C)}{\partial y} + \frac{\partial(y_z C)}{\partial z} + \sum_s q_s C_s + \sum_n R_n$$

C = dissolved concentration of the contaminant species, gm^{-3}.

x,y,z = distance along the respective Cartesian coordinate axis, m.

t = time, s.

q_x, q_y, q_z = Darcy velocities, in the directions x, y, and z, ms^{-1}.

θ = porosity, dimensionless.

q_s = volumetric flow rate per unit volume of the aquifer from sources (positive) and sinks (negative), s^{-1}.

C_s = concentration of the contaminant species in water that is added or removed, gm^{-3}.

D_{xx}, D_{xy}, D_{xz}, D_{yx}, D_{yy}, D_{yz}, D_{zx}, D_{zy}, D_{zz} = Components of the dispersion tensor, m^{2}s^{-1}.

R_n = chemical sink/source term for n^{th} reaction, $\sum_n R_n$ represents the rate of change in solute mass due to $n = 1, 2, \ldots, N$ chemical reactions.

In the above formulation, the dissolved concentration C is a time varying scalar field (a function of x, y, z, and t) which represents the concentration at some location (x,y,z) in a groundwater system at some time instant (t). The right-hand-side of the equation describes the net loss of pollutant mass from the control volume (x,y,z) due to mass outflows and inflows. The terms in the right-hand-side represent the mass flows caused by four different hydrological and external processes: advection, dispersion, chemical reactions and external sources and sinks. A detailed discussion on the components of the equation is given in Appendix A.

Moreover, this transport equation assumes that the change in concentration that occurs in some location in the aquifer, at some instance in time, is a function of the following factors.

1. Properties of the subsurface strata (affect θ, D_{ij}, q_i, and R_n).
2. Groundwater flow in the aquifer (affects D_{ij} and q_i). The flow terms (q_i) are obtained from a groundwater flow simulation as discussed in Appendix A.
3. Properties of the contaminant species (affect D_{ij} and R_n).
4. Sources and sinks of the contaminant species (affect q_s, C_s, and q_i)

The above general solute transport equation is used to study nitrate transport in groundwater. Advective transport is dominant in most aquifers (Hadfield, 2008). Hence if the external sources are fixed, the groundwater flow regime which determines q_i is the main factor that affects the changes in concentration. A detailed discussion on the components of the equation is given in Appendix A.

2.5.3 Mathematical Models of Contaminant Transport in Groundwater

A mathematical model of a solute transport system consists of (1) the governing equations discussed above, (2) initial conditions specifying the initial level of contamination in the model domain, i.e., the concentration when t = 0, and (3) boundary conditions specifying the ways the model domain communicates with areas outside the model domain. Boundary conditions include fixed head or concentration boundaries and no-flow boundaries. By solving the mathematical model, we can obtain the concentration distribution over space and time.

2.5.4 Computer Codes for Contaminant Transport Simulation

The term transport simulation usually refers to the use of computer programs to develop and solve the mathematical models of contaminant transport. Many computer codes have been developed to obtain approximate solutions to the partial differential equation of contaminant transport in groundwater, or sometimes the coupled equations of groundwater flow and contaminant transport. MT3D (Zheng, 1990) is a three-dimensional solute transport code which solves the transport equation using the flow terms obtained from the solution of the groundwater flow model. MT3D can be linked to a groundwater flow model, from which it can obtain the flow solution. MODFLOW (Harbaugh, Banta, Hill, & McDonald, 2000) is the most commonly used computer code to solve groundwater flow problems. MF2K-GWT (USGS, 2006) is an enhanced version of MODFLOW-2000 which simulates both solute transport and groundwater flow.

2.5.5 Nitrate Transport Modelling

Nitrate transport in groundwater is usually modelled with MT3D and MODFLOW (Almasri & Kaluarachchi, 2005; Conan, et al., 2003; Molenat & Gascuel-Odoux, 2002; D. S. Morgan & Everett, 2005). MT3D can model advective, dispersive, and reactive transport of nitrate in groundwater. Usually, nitrate does not form insoluble minerals, does not precipitate, and is not naturally adsorbed; hence, the only process by which nitrate is removed from groundwater is chemical transformation (Conan, et al., 2003). With MT3D, these reactions can be modelled as first-order irreversible rate reactions (Appendix A).

Rather than using standard packages such as MT3D, some studies of nitrate transport use customised (or regionalized) mathematical models which simplify the general transport equation (for example, by assuming one-dimensional and purely advective transport) to simulate nitrate transport in groundwater (Barkle & Wang, 2005; Hoffmann et al., 2006). However, the validity of a simplified model is limited to the specific problem domain and the assumed hydro-geological conditions.

The advantage of customised models is that they can be integrated with the simulation models of other processes in the nitrogen cycle, rather than separately simulating nitrate transport in groundwater. For example, the integrated models proposed by Flipo, Even, Poulin, Théry, and Ledoux (2007) and Wriedt and Rode (2007) simulate both soil nitrogen dynamics and nitrate transport in groundwater. These models are used to predict the effects of alternative agricultural management scenarios on water quality.

The preceding section was about modelling nitrate transport in groundwater, because groundwater is the major path of nitrate dissemination over space and time. However, tools and techniques are available for detailed modelling of nitrate transport in surface water. One such tool is QUAL2K (Pelletier & Chapra, 2004) which can model the transport of multiple reactive pollutants in streams. QUAL2K can model the variations in nitrate level along the streams.

2.6 Essentials of Nitrate Pollution Control

Given the complexity of the way nitrate pollution works, nitrate pollution control is a multidisciplinary task, requiring a collaborative effort of hydrologists, economists, environmental authorities, and all other stakeholders. Some essential considerations in nitrate control are discussed below.

2.6.1 Integrated Catchment Based Approaches

Groundwater and surface water pollution from point and nonpoint sources are inter-connected. If only the direct discharges into the streams and lakes are monitored and controlled, nitrates loaded into the aquifers which take a long time to appear in the streams and lakes, can go beyond control. If only nitrate loading into the aquifers from nonpoint sources were monitored and controlled, point source discharges into the streams and lakes may go beyond control. Therefore, integrated watershed based approaches or catchment scale approaches are highly recommended for the control of nitrate pollution (O'Shea, 2002).

2.6.2 Manageable and Unmanageable Sources

For efficient pollution control, it is important to identify all the manageable and unmanageable pollution sources in the problem domain. Manageable sources are those which can be controlled by human intervention.

Agriculture, the number one source of nitrate in groundwater, is a manageable source. Fertilizer, dairy manure, livestock effluents, contaminated irrigation water, dairy lagoons, and most other hazardous agricultural practices are manageable. Nonagricultural manageable sources of groundwater nitrate include onsite wastewater disposal, leaky sewers, and solid waste disposal in landfills.

Even though the sources of nitrate leaching into groundwater are manageable, once nitrate is in groundwater, it becomes highly unmanageable. The hydro-geological processes which determine when and where nitrate goes with groundwater are mostly beyond human control. Therefore, *nitrate in the upper-catchment groundwater is an unmanageable source of nitrate in the lower-catchment groundwater and groundwater seepage is an unmanageable source of nitrate in surface water*.

All industrial and municipal point sources that discharge nitrate into surface water bodies are considered as manageable sources. Storm water runoff into streams and lakes (surface and near sub-surface runoff) is also controllable to some extent via land management and drainage systems. Rainwater, head waters, aquatic plants and species (birds, water fowls, etc.) are minor unmanageable sources of nitrate in surface water.

Virtually all sources are controllable to some extent, but those sources which are difficult and too expensive to control are considered as unmanageable sources. For example, there are methods and techniques to manage groundwater nitrates (building wetlands or laying underground barriers or absorbers to reduce nitrate flow from the region).

2.6.3 Environmental Standards

The environmental objective of nitrate control is to achieve sustainable nitrate levels in groundwater and surface water. National and international environmental authorities have set water quality standards (or maximum acceptable nitrate levels in water) to meet human and ecosystem health needs.

According to New Zealand's national water quality guidelines, the maximum acceptable nitrate concentration in drinking water is 50 mg/l (MFE, 2009). The water quality guidelines specify maximum acceptable concentrations of nitrate (NO_3), nitrate-nitrogen (NO_3-N), or total nitrogen (T-N), because in water, nitrogen may be present in other forms such as ammonia (NH_3). A nitrate concentration of 50 mg/l is the same as a NO_3-N concentration of 11.3 mg/l (multiplying by a conversion factor of 0.226). An internationally accepted T-N standard for drinking water is 10 mg/l. As discussed earlier, nitrate is the most widespread form of nitrogen found in water and it is usually assumed that NO_3-N concentration = T-N concentration.

For streams and lakes, the maximum acceptable values are more stringent to protect the ecosystem balance. For New Zealand streams, the maximum acceptable nitrate concentration in upland streams is 0.71 mg/l while the same in lowland streams is 1.95 mg/l (MFE, 2009).

2.6.4 Environmental Monitoring

Given the environmental standards, nitrate concentration in groundwater and surface water should be continuously monitored to ensure that the standards are met. It is practically impossible to monitor and control nitrate level at all the points in an aquifer or a surface water body. Therefore, catchment planners usually select a few monitoring points to indicate the overall water quality in the catchment. These monitoring points are called "receptors." By definition, a receptor is a water body or a point on a water body where water quality is monitored.

2.6.5 Models of Source Receptor Relationships

To impose controls on the sources so that the water quality standards at the receptors are met, the regulators should know the relationship between the discharges at the source locations and the concentrations at the receptors. Numerical models of source-receptor linkages play an important role in controlling nitrate pollution.

2.6.6 Cost Efficiency

The largest nitrate dischargers are commercial entities like large scale farms. Inevitably, nitrate discharge controls would hurt their economic performance. For example, restrictions on stocking rates, fertilizer use, and other nutrient management practices may wipe millions of dollars from the agricultural properties (Stringleman, 2007). Therefore, management alternatives for controlling nitrate pollution should be evaluated based not only on the environmental performance, but the cost of those alternatives. Control efforts should be implemented in such a way that they minimise the economic damage to commercial entities, so that they can remain competitive in the global market place.

2.7 Policy Alternatives for Controlling Environmental Pollution

Environmental protection is a national responsibility and governments use different policies to control environmental pollution. There are three major types of pollution control policies: direct controls, pollution taxes, and tradable permits (Ragan, 2001).

2.7.1 Direct Controls

Direct controls, also known as command-and-control policies, specify exactly what the consumers or polluting firms can do. They enforce quantitative limits on discharges, use of natural resources, or application of polluting chemicals. Usually, these limits are uniform standards across all consumers or firms, regardless of the differences in pollution reduction costs that individual firms may have. However, control costs may vary across firms owing to the variations in technologies adopted, equipment used, plant design, processes, and location. Consequently, requiring all firms to reduce pollution to the same level may be expensive because some firms incur relatively high costs in pollution reduction.

2.7.2 Taxing

Pollution taxes or charges require the polluters to pay a tax for every unit of pollution they produce. The history of tax policy for pollution control dates back to the 1920's, when Arthur C. Pigou first suggested that firms should pay for the harmful effects of their operations (Pigou, 1932). Pigou identified pollution as an economic externality. Externalities arise when the economic activities of some parties cause incidental injuries or benefits to other parties not directly involved in those activities (Baumol & Oates, 1975). The commercial operations of some firms cause pollution which harms many other people. Therefore, pollution is a negative externality. Pigou suggested taxes to discourage negative externalities and subsidies to encourage positive externalities.

A rational firm will reduce its pollution to a level where its marginal abatement cost equals the tax rate. However, selecting the right tax rate is the biggest challenge associated with this system. Ideally the tax rate should be set “equal to the marginal benefits of cleanup at the efficient level of cleanup”, but the regulator does not have prior knowledge of how the polluters will respond to a given tax rate (Stavins, 2003). Examples of pollution taxes include (Stavins, 2003): carbon tax schema adopted by the OCED (Organization of Economic Cooperation and Development) countries; unit charge systems for collecting municipal waste in the United States; and emission levies charged in China for air and water pollutants such as sulphur dioxide and carbon monoxide.

2.7.3 Tradable Permits

Tradable permits are licences issued by the government or a representative authority which allow the holder to produce a specified amount of a specified type of pollution for a specified period.

The foundation for the theory of tradable permits was laid by Coase (1960) who challenged the Pigovian solution to the externalities. Coase proposed the tradable property rights approach as a better means of dealing with negative externalities. The popular Coase theorem states that if property rights are well defined, negotiation is costless, and transaction costs are negligible, then the parties will negotiate an efficient solution (a jointly maximising outcome) to the externality and no taxation is necessary. The theorem implies that tradable permits lead to cost efficient distribution of pollution rights if they are clearly defined and negotiation is possible.

Coase’s thoughts initiated a major shift in the direction of pollution control policy from regulation to market approach and opened up a new discussion on tradable pollution permit systems (Atkinson & Tietenberg, 1982; Dales, 1968; Montgomery, 1972; Tietenberg, 1980).

The pioneer of pollution permit trading systems is the United States. The US Environmental Protection Authority authorised the lead emission trading program in the 1980s to provide gasoline refineries with greater flexibility in meeting the emission standards. The United States allowed the well known sulphur dioxide allowance trading program for acid rain control in 1990 under the Clean Air Act Amendment. Due to its continuing success, the sulphur dioxide trading system is considered as a benchmark for pollution trading systems.

Most air pollution permit trading programs work in a similar manner. The government decides the total allowable level of pollution, which is distributed among polluters via pollution permits. The market for permits determines their price. Given the price, the firms which have low abatement costs will sell their permits, collect some money, and reduce their pollution. Those polluters who have higher abatement costs will buy permits at the market price, and save the cost of pollution reduction. Thus pollution will be reduced by those who can do it at least cost, and the required reduction will be achieved at the least total cost.

A command and control strategy could also achieve this cost-minimising allocation of control burden, if the regulator knew the marginal abatement costs of each polluter and had authority to impose different levels of control on each polluter based on the abatement costs. This policy needs the regulator to have perfect information about the polluter's costs. In contrast, a market achieves the cost minimising allocation of permits without requiring the regulator to have this information.

Despite the economic theory which favours tradable permits, all types of pollution control methods are present all over world (Stavins, 2003). Water pollution permit trading programs have not yet achieved significant success compared to air pollution permit trading programs, but a few exceptions are present. For example, two nutrient trading programs in the Minnesota River Basin in the United Sates (Fang, Easter, & Brezonik, 2005) and a salinity trading program in Hunter River valley in Australia (Environmental Protection Authority, 2003) have reported good environmental and economic performance.

Chapter 3

3 Optimal Control of Water Pollution

3.1 Introduction

This chapter is about the non-market based (mainly command-and-control) approaches to efficient control of water pollution. We discuss both the general approaches to water pollution control and the specific approaches to nitrate pollution control. First, we discuss the theoretical concepts related to optimal pollution control. We discuss some early applications of mathematical programming techniques to control point source water pollution and some recent applications of the simulation-optimisation approach to water pollution control from both point and nonpoint sources. The chapter highlights the requirements, limitations, and benefits of different non-market based mechanisms proposed for the optimal control of nitrate pollution.

3.2 Optimal Control Theory

Optimal control of pollution refers to the allocation of pollution rights or pollution reduction (abatement) responsibilities so that the environmental quality standards are met at the least cost to society. The pre-requisite for optimal pollution control is that the regulator knows the magnitude of benefits derived by each polluter from each unit of pollution produced (or cost incurred by each polluter from each unit of pollution reduction required). If such private information is available, the environmental regulator may model the optimal pollution control problem and solve it using some optimisation technique to find the optimal allocation of pollution rights or pollution reduction responsibilities. The models may vary depending on the type of pollutant considered and the natural resources being polluted. However, all optimal pollution control models have some characteristics in common.

3.2.1 A Formal Statement of the Optimal Pollution Control Problem

Let us assume that a regional community wishes to protect their environment (water or air) from some pollutant species. The region has $n = 1, 2, \ldots, N$ sources of the pollutant and $m = 1, 2, \ldots, M$ receptors where the level of pollution is measured and controlled. Environmental quality standards at the receptors are given as $q_1, q_{2,} \ldots, q_M$. The environmental damage at each receptor m caused by each source n is a function of the source emission (the amount of the pollutant released into the environment, water or air) given by $D_{nm}(e_n)$. The regional environmental regulator who represents the society's interest would like to find a set of emission levels $e_1, e_2\ldots, e_N$ for the N sources, which minimise the joint total pollution control cost of the N sources. The pollution control cost of each source (the cost of adopting emission level e_n) is considered as a function of emission represented by $C_n(e_n)$. The regulator's problem can be stated as follows.

Minimise $\quad \sum_n C_n(e_n)$

Subject to $\quad \sum_n D_{nm}(e_n) \leq q_m$ for all m.

$e_n \geq 0$ for all n.

A distribution of pollution rights or abatement responsibilities which results in such an optimal emission vector is known as an optimal allocation of pollution permits.

The above is a generalized version of the air pollution control model discussed in Montgomery (1972), McGartland and Oates (1985), and many others. It assumes that both emission and environmental damage occur at the same time, and therefore, the optimal control model is free from any inter-temporal considerations. The assumption holds for many water pollution control problems, mainly when only surface water pollution from point sources is considered, but it may not hold when groundwater and surface water pollution from nonpoint sources are considered. The model also assumes that the environmental standards at the receptors are given after all unmanageable sources are accounted for.

The cost functions are usually assumed to be convex, monotonically decreasing with emission (the higher the emission, the lower the abatement cost), and the response functions are assumed to be linear (Montgomery, 1972). Under these two conditions, the above pollution control model becomes a convex optimisation problem for which efficient solution algorithms are available. If the cost functions are linear too, the problem becomes a well-behaved, solvable linear programming problem.

3.2.2 Optimal Control of Nitrate Pollution

Due to the delayed nature of nitrate pollution, the above general pollution control model needs some modifications to accurately describe the nitrate control problem. The time lags between nonpoint source emissions and the occurrence of environmental damage (appearance of discharged nitrates at the receptors) raise temporal considerations. Therefore, the model should be extended to enforce environmental standards over time. The regulator's problem now is determining the maximum emission levels for the N sources, e_1, e_2…, e_N in some single management period $t = t^0$ so that the environmental standards over some $t = t^0$, t^0+1, t^0+2, …, t^0+T time periods are met at least cost to society. The regulator has to decide the total allocations for the management period t^0, $q_{1t^0}, q_{1(t^0+1)}, \ldots, q_{1(t^0+T)}, \ldots, q_{Mt}, q_{M(t^0+1)}, \ldots, q_{M(t^0+T)}$, the maximum level of pollution that the source emissions in management period t^0 can jointly cause at each receptor m in each time period t. Total allocations for any upcoming management period should be set taking into account the unmanageable sources and expected emissions in the future (after the management period). The model presented below is for a single management period t^0, but can be adapted for multiple management periods with minor changes.

Minimise $\sum_n C_n(e_n)$, subject to:

$\sum_n D_{nmt}(e_n) \leq q_{mt}$ for all m and t.

$e_n \geq 0$ for all n.

The above formulation models the optimal *emission* levels for the N sources. Hence, for the nonpoint sources of nitrates, e_n is usually considered as the amount of nitrate loaded into a groundwater aquifer (we used the term emission to refer to the amount of a pollutant released *into* the atmosphere or a water body, not the amount of a pollutant released from a source). However, the nonpoint sources, mainly agricultural sources, cannot always control nitrate emissions (or loading) directly. What they can control are some variables such as fertilizer application rate, stocking density, and irrigation intensity, which eventually determine the actual nitrate loadings. In such situations, the above model is applicable only if the sources can relate the required optimal loading levels to their controllable variables, and if the cost functions can be expressed in terms of nitrate loading. Otherwise, a nitrate control model should optimise a set of recognized source control variables l =1, 2, …, L for the N sources relative to the joint total pollution control cost, the cost of adopting the pollution control variables x_{1n}, x_{2n}, …, x_{Ln} for the N sources. The model requires knowledge of the relationship between the control variables and the nitrate loading.

Assume the nitrate loading caused by adopting x_{1n}, x_{2n}, …, x_{Ln} variables by source n is given as $F_n(x_{1n}, x_{2n}, \ldots, x_{ln})$ and the cost of adopting those variables is given as $C`_n(x_{1n}, x_{2n}, \ldots, x_{ln})$. Then the optimal nitrate control problem is as below.

Minimise $\sum_n C`_n(x_{1n}, x_{2n}, \ldots, x_{Ln})$, subject to:

$e_n = F_n(x_{1n}, x_{2n}, \ldots, x_{Ln})$ for all n.

$\sum_n D_{nmt}(e_n) \leq q_{mt}$ for all m and t.

$e_n \geq 0$ for n.

Previous research has observed that both $C`_n$ and F_n are most likely to be non-linear (Nikolaidis, Heng, Semagin, & Clausen, 1998; Peña-Haro, Pulido-Velazquez, & Sahuquillo, 2009). Hence, a nitrate control model which optimises the source control variables rather than the emissions can be non-convex. As a consequence, many nitrate control studies have tried to optimise the emissions, expecting the sources to adopt their variables accordingly. Today, agricultural sources do actually have the capability of adopting their farming practices to control the nitrate loading because they have access to on-farm nutrient management models such as OVERSEER (discussed in section 2.4.3).

3.3 Approaches for Optimal Control

An optimal nitrate control policy can be devised and implemented if reliable information is available to model the optimal control problem, if the problem can be solved efficiently using available optimisation tools and techniques, and if the economic, political, or social environments are flexible enough to accept the optimal solution. Otherwise, the acceptable policy alternatives are tested against the cost and environmental performance to choose a second best solution (Schou, Skop, & Jensen, 2000; Semaan, Flichman, Scardigno, & Steduto, 2007; Yadav & Wall, 1998). Regardless of the social and political barriers for the implementation of a mathematically optimal policy, many researchers have modelled the problem on regional scales to obtain proven optimal solutions. In the subsequent sections, we describe a variety of optimisation approaches adopted for the optimal control of water pollution in general and optimal control of nitrate pollution in particular.

3.3.1 Optimisation Techniques

A variety of optimisation techniques have been used to solve water pollution control problems, but linear programming (LP) is most commonly used because of its simplicity and availability of solution methods. When linear programming is not applicable, other mathematical programming techniques such as nonlinear programming (NLP), mixed-integer linear programming (MILP), dynamic programming (DP), and heuristic search techniques such as genetic algorithms, tabu search, and artificial neural networks have also been used in solving water quality management problems (Greenberg, 1995; Zheng & Bennett, 2002).

3.3.2 Early Applications of Mathematical Programming

The first application of mathematical programming for environmental pollution control appeared in the early nineteen sixties (Greenberg, 1995). Lynn, Lorgan, and Charnes (1962) were the first researchers to use an LP to determine the optimal levels of treatment required by a set of treatment plants to minimise the total cost of sewage treatment while meeting the environmental standards on biochemical oxygen demand (BOD) in the effluents. The LP minimised total treatment cost subject to three constraints on mass balance at each node (input = output + reduction by treatment), pollutant input into the system, and the maximum amount of BOD allowed in the output from the system.

In 1964, Thomann and Sobel (cited in Greenburg, 1995) developed an LP to control stream water pollution. This LP was formulated to determine the levels of treatment required by the point source dischargers to maximise the ratio of benefits to costs subject to flow balance equations and water quality constraints (maximum allowed levels of BOD and dissolved oxygen deficit in water).

In 1966, Liebman and Lynn (cited in Greenburg, 1995) developed the first DP model to minimise the cost of sewage treatment subject to environmentally acceptable dissolved oxygen levels. In 1968, Clough and Bayer (cited in Greenburg, 1995) developed an NLP for optimal wastewater treatment. Many other applications of mathematical programming techniques in water pollution control during the nineteen sixties and seventies are described in Greenburg (1995).

The early work was mostly on surface water quality and wastewater treatment optimisation. Aguado, Remson, Pikul, and Thomas (1974) were the first to present an LP to optimise groundwater extraction. In their management optimisation model, they included the finite difference approximations of the differential equations that describe groundwater flow (Appendix A), as constraints in the model. Gorelick and Remson (1982) modelled an LP to control groundwater pollution using a method called the "response matrix technique" (discussed in section 3.3.3) to include the physical characteristics of solute transport in groundwater in their model. The LP maximised the total disposal of waste solutes subject to groundwater quality standards. They also presented an MILP to determine how the waste disposal facilities should be located so that groundwater quality was maintained at least cost.

3.3.3 The Response Matrix Technique for Groundwater Quality Management

Most of the early groundwater pollution control studies, for example Aguado et al. (1974) and Gharbi & Peralta (1994), used mathematical models that simulate groundwater flow and solute transport embedded into the management optimisation models. Groundwater quality management models based on embedded numerical formulations of the underlying physical systems are usually known as “embedded models.” Gorelick and Remson (1982) presented a new approach called the response matrix technique to associate the physical aspects of solute transport in groundwater quality control models. This method is relatively simple compared to the embedded approach, because it uses a matrix of constants, rather than complex numerical formulations to describe the physical transport system.

Gorelick and Remson used numerical simulations of solute transport in groundwater to obtain the matrix of coefficients which measured “the increase in concentration that occurs at each constraint location, in each simulation time step, from one unit of waste loading at each source location during each management period.” This matrix is called the source-concentration “response matrix”. As shown below, the response matrix is used in the management model to specify the water quality constraints over time.

The problem was to maximise the waste loading into an aquifer from $j = 1, 2, \ldots, J$ waste injection wells (sources) over $k = 1,2, \ldots, K$ management periods (injection periods), meeting the water quality standards at i=1, 2, …, I water supply wells (receptors) over $t = 1, 2, \ldots, T$ time steps in the time frame of the problem (water quality monitoring time steps). The LP model was given as follows.

Maximise $\sum_j \sum_k f_{jk}$, subject to:

$[\mathrm{R}][f_{jk}] \leq [c_{it}]$.

$[f_{jk}] \geq 0$.

f_{jk} = solute injection rate at injection well j during management period k. This is the product of waste water injection rate W_{jk} and the concentration in waste water C_{jk}.

$[f_{jk}]$= column vector of $n = J \times K$ elements, f_{jk}.

c_{it} = water quality standard imposed at water supply well j at time step t.

$[c_{it}]$ = column vector of $m = I \times T$ elements, c_{it}.

[R] = rectangular (m by n) unit source-concentration response matrix.

In the set of water quality constraints ($[R][f_{jk}] \leq [c_{it}]$), the concentration at each receptor in each monitoring time step is calculated as the sum of the effects (concentration responses) of injection by each source in each management period. Concentration response is calculated as the product of the relevant response coefficient and the source injection rate. Thus the response matrix technique is based on linear programming superposition which guarantees linear water quality constraints. The principal assumption is that "each source of groundwater pollution has a constant volumetric disposal rate W_{jk} and therefore a constant influence on the groundwater flow velocity field." Since the solute injection rate is the product of solute source flux and concentration ($W_{jk} \times C_{jk}$), treating both factors as variables creates non-linearity with respect to solute transport, because advective and dispersive transport depends on both concentration and velocity.

With respect to nitrate leaching from diffuse agricultural sources, the volumetric effluent disposal rate is the rate of groundwater recharge from the source area (water percolation rate). Areal recharge depends on two factors, rainfall and irrigation. Superposition would hold if and only if both rainfall and irrigation are fixed in each management period. But a constant recharge rate over the management periods is not a necessary requirement[2]. Usually a fixed rate of annual recharge is calculated based on annual rainfall assuming that irrigation water seepage is negligible compared to natural rainwater recharge (Hadfield, 2008; Rekker, 1998).

The response matrix technique has become popular since the early eighties. Today, this method is commonly used to solve groundwater quality management problems (D. S. Morgan & Everett, 2005; Peña-Haro, et al., 2009). Since the response matrix is

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[2] This means that the formulation does not require the groundwater flow terms to be constant over the whole simulation (over the whole period covering the management periods and the monitoring time steps). Hence, the response matrix technique is applicable even if the groundwater flow system is not in a steady state.

usually obtained from simulations, the applications of the response matrix technique are usually discussed under the broader category of literature on simulation and optimisation approaches for water pollution control.

3.4 Simulation and Optimisation Approach for Water Pollution Control

As we discussed in the introduction, the fate of point and nonpoint source emissions are determined by complex hydro-geological processes. These physical transport systems affect the level and timing of water pollution caused by the sources. Therefore, a significant portion of research has focused on incorporating the environmental simulations (models that simulate the behaviour of pollutants in the environment) in the management models designed for the optimal control of water pollution. Approaches which utilize both simulation and optimisation techniques to find the best methods, policies, or strategies for controlling water pollution are known as simulation and optimisation approaches (Almasri & Kaluarachchi, 2005; Ejaz & Peralta, 1995; D. S. Morgan & Everett, 2005; Peña-Haro, et al., 2009). Several factors including the huge cost associated with pollution control and reduction, the appeal in controlling nonpoint sources which have dispersed and delayed affects, and rapid development of computer technology in both hardware and software have motivated the simulation-optimisation approach (Zheng & Bennett, 2002).

Under the simulation-optimisation framework, simulations predict the level of water pollution that occurs from possible management scenarios or alternatives (for example, limiting nitrogen fertilizer application rate to 70 kg/ha/year) and optimisation techniques determine the least costly or most profitable alternative subject to the water quality goals specified as constraints over the management alternatives (for example, keeping the nitrate concentration below 50 mg/l in a groundwater well). The coupling of simulation and optimisation is achieved via the embedded approach, the response matrix technique, or both.

However, the prerequisite for the simulation-optimisation framework is the availability of well calibrated, reliable contaminant transport simulations (Zheng and Bennett, 2002). In the presence of uncertainty in simulation results, which provide input parameters to the management models, stochastic optimisation methods are used.

We next discuss a few of the proposed simulation-optimisation approaches, as representative of their applicability in controlling point and nonpoint source water pollution from nitrates and other pollutants.

3.4.1 Response Matrix Technique Combined with Embedded Formulations (for General Water Pollutants)

Ejah and Peralta (1995) presented a mathematical programming model to determine the optimal conjunctive water use from a stream-aquifer system, and waste loading into the stream from a sewage treatment plant (STP), that satisfy environmental quality requirements. The model included conflicting objectives of maximising water supply from groundwater extraction and surface water diversion and maximising the waste loading into the stream. To maintain water quality, constraints were imposed on groundwater pumping, surface water diversion, aquifer head, stream reach outflow, stream aquifer interflow, and concentration of modelled constituents at the control locations. With respect to waste loading, the variable optimised was the total waste loading from the STP, but since the STP discharge contains many water pollutants such as nitrogen, phosphorus, and dissolved solids, constraints were imposed on each constituent separately.

Ejah and Peralta used a groundwater hydrology model (a MODFLOW model) to determine the spatial effects of pumping from each pumping location on aquifer heads, stream flows, and stream-aquifer interflows as influence coefficients (response matrix coefficients)[3]. They also developed a set of regression equations to represent the constituent transport in the stream. The regression equations were calibrated using a stream water quality model, QUAL2K.

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[3] The response matrix technique has been proposed as a method to describe solute transport in groundwater (Gorelick & Remson, 1982), but in this work, the response matrix is used to describe the flow of groundwater itself.

The influence coefficients and regression equations were applied in a multi-objective optimisation model. The paper states that the mathematical program was non-linear, and that should be due to the non-linearities in the regression equations. The multi-objective programming problem was reduced to a single-objective NLP using the E-constraint method and solved using the MINOS solver.

Ejah and Peralta contributed to water pollution control optimisation in two ways. First, they presented an integrated optimisation model for controlling point source pollutant loading (single source) and extraction of both surface water and groundwater. Second, they used the response matrix technique and embedded technique where each technique is best applicable, the response matrix technique to describe the groundwater flow system, and the embedded technique to describe the solute transport in surface water. Nothing is mentioned about the temporal issues, meaning that they assumed the responses to groundwater abstraction occur with no significant time delay.

3.4.2 Discharge Response Coefficients (for Nitrate)

Morgan and Everett (2005) described a simulation-optimisation approach to determine the optimal levels of nitrate loading reductions (relative to status-quo build out loading) required from decentralized individual waste water treatment systems (DWTS) in the La Pine area of Oregon, United Sates, to meet groundwater and surface water quality standards. They used a groundwater model to simulate nitrate transport and obtain a response matrix which relates the source (zonal) nitrate loading to the concentration at each control point (by location and depth) and nitrate discharge into a stream via groundwater seepage. The simulation models were developed using MODFLOW and MT3D. Due to the limited scale of the simulation model, it was not feasible to manage individual DWTS, so they were grouped into management zones.

The response matrix was then used in a linear programming model which determined the least-cost distribution of nitrate loading reductions required by 97 management zones in La Pine. The constraints were the minimum reductions required in (1) groundwater nitrate concentration at each control location and (2) nitrate discharge into each stream reach (segment), and (3&4) maximum and minimum loading reductions required in each management zone. The model used is given below.

Indices:

i = management area. j = management block = 1 for the block of existing homes or 2 for the block of future homes (proposed); these are two blocks of areas in each management zone.

m = concentration control location. k = concentration control depth. r = stream reach.

Parameters:

U_j = unit cost of nitrate loading reduction from existing or future homes, dimensionless.

rc_{ijmk} = the increase in concentration at constraint location m and depth k, caused by unit (1 kg/day) loading from block j in management area i, (mg/l)/(kg/day).

rd_{ijr} = the increase in nitrate discharge into stream reach r, caused by unit (1 kg/day) loading from block j in management area i, dimensionless.

$CRmin_{mk}$= the minimum concentration reduction required at constraint location m and depth k. This is the difference between the maximum allowable concentration and the status quo built out concentration, mg/l.

$DRmin_r$= the minimum groundwater discharge nitrate load reduction required in stream reach r. This is the difference between the simulated status-quo build out discharge to reach r (units of kg/d) and the maximum allowable discharge load to reach r, kg/d.

$NRmin_j$ and $NRmax_j$ = minimum and maximum loading reduction limits for existing and future homes (kg/day).

Decision variables:

NR_{ij} = nitrate loading reduction required by type j homes in management area i, kg/day.

Model:

Minimise $\sum_i \sum_j U_j NR_{ij}$, subject to:

$rc_{ijmk}\, NR_{ij} \geq CRmin_{mk}$

$rd_{ijr}\, NR_{ij} \geq DRmin_r$

$NRmin_j \leq NR_{ij} \leq NRmax_j$

Morgan and Everett furthered the use of the response matrix technique in two ways. First, they used two types of response coefficients: concentration response coefficients, measuring the increase in concentration at each groundwater monitoring point; and discharge concentration coefficients, measuring the increase in nitrate discharge into the stream, due to unit nitrate loading from each management zone. Second, they reduced the number of rows in the matrix, by considering the equilibrium responses rather than the response at each time step simulated. To obtain these coefficients, they simulated loading from each management zone until equilibrium concentration levels were achieved at each control point. However, the mechanism of imposing constraints on equilibrium responses suits only if the same loading levels can be maintained over a relatively long time, because reaching equilibrium may take a long time (in this case 100 years).

Comparing the cost of the optimal solution with the cost of uniform control scenarios (requiring all management zones to reduce nitrate loading by the same amount), Morgan and Everett showed that the optimal solution leads to significant cost savings.

3.4.3 Integrated Simulation-Optimisation Models (for Nitrate)

Amalsri and Kaluarachchi (2005) presented an integrated methodology for optimal management of nonpoint source nitrate loading. They used two physical models which simulated soil nitrogen dynamics and nitrate transport in groundwater coupled with an optimisation module to determine the maximum sustainable on-ground nitrogen loading for each region, which satisfied water quality standards. Once the optimal loading for each region was calculated, a series of protection alternatives were evaluated using a decision analysis module to select the best protection alternative.

The optimisation problem was stated as follows.

Indices:

i = drainage (management zone): 1, 2, …, N.

k = receptor: 1, 2, …, N.

Parameters:

δ_M and δ_F = weighting coefficients for manure and fertilizer loadings.

C^t_k= maximum monthly nitrate concentration, at the last year of the simulation period, t, at receptor k.

Decision Variables:

NM_i and NF_i = sustainable annual manure and fertilizer application rates for drainage i respectively, lbs.

Model:

Maximise $\delta_M \sum_i NM_i + \delta_F \sum_i NF_i$ subject to $C^t_k \leq MCL$ for k = 1, 2, …, N.

Amalsri and Kaluarachchi used an integrated simulation model to relate the sources and receptors. They estimated the spatial and temporal distribution of on-ground nitrogen loading using the National Land Cover Database (NLCD) prepared by the US Geological Survey. With the on-ground nitrogen loading as an input, soil nitrogen dynamics were simulated using the framework adopted in the Nitrate Leaching and Economic Analysis Package (NLEAP). The final output from the soil nitrogen model was the spatial and temporal distribution of nitrate leaching to groundwater. With leaching as diffuse sources, nitrate fate and transport in groundwater were simulated using MODFLOW and MT3D. The output was the resulting nitrate concentrations at the receptors.

Amalsri and Kaluarachchi used genetic algorithms (GM) to find an optimal solution to the above problem. To save much of the time taken to run the coupled physical simulation every time a candidate solution is evaluated, they used an artificial neural network (ANN) as a proxy to expedite the search. The ANN was trained and tested using the integrated simulation model which was then replaced by the ANN.

This integrated nitrate loading and transport model is a good approach, especially in the presence of non-linearities in the relationships between the management variables, in this case fertilizer and manure application rates, and the concentration at the receptors. However, the ability of the optimisation model to sufficiently represent the spatial and temporal aspects of the nitrate pollution problem depends on the choice of the receptors and the simulation period, but they do not clearly recommend how to select those. Any optimal solution obtained from this model may not be able to ensure the attainment of water quality standards over time, because, as discussed in section 2.6.2, the current concentration distribution in the aquifer has significant effects on future nitrate concentrations; and the effects of nitrates already in the aquifer are ignored in the model proposed by Amalsri and Kaluarachchi.

3.4.4 Nonlinear Optimisation Models (for Nitrate)

Peña-Haro et al. (2009) proposed a simulation-optimisation framework for the optimal management of groundwater nitrate pollution from agriculture. They modelled the optimal rates of nitrogen fertilizer application over time for spatially distributed crop areas with a single distinct crop assigned to each area. The economic benefit from growing each crop was given as a function of crop revenue and cost of water and nitrogen fertilizer. The authors assumed that the crop production and nitrate leaching from each crop were quadratic functions of nitrogen fertilizer and irrigation water applications, and that other factors, such as soil properties, climate, and geography were uniform over the whole catchment area. Nitrate leaching from crop areas was related to the concentration at the groundwater control sites using a response matrix. To apply superposition, they considered aquifer recharge from each crop area to be constant and independent of irrigation. The management model was given as follows.

Indices:

c=crop or crop area.

t= year in which fertilizer is applied.

s= simulated (monitoring) time step.

o = concentration control point.

Parameters:

A_c = area cultivated in the crop area *c,* ha.

p_c = crop price, €/kg.

p_n= nitrogen price, €/kg.

p_w = irrigation water price, €/m^3.

r = annual discount rate.

a, b,…, l = coefficients of the crop yield and leaching functions calibrated from an external agronomic simulation model.

r_t = the water that recharges the aquifer (m^3/ha) at time t.

[RM] = a rectangular $m \times n$ source-concentration response matrix. Response coefficients were obtained from a groundwater solute transport simulation using MODFLOW and MT3D. The number of columns n equals the number of crop areas (sources) times the number of years within the planning horizon (years in which fertilizer is applied). The number of rows m equals the number of control sites (receptors) times the number of simulated time steps in the time frame of the problem (years in which water quality standards apply).

[q_{os}] = a column vector of water quality standards imposed at the control sites over the simulation time (kg/m^3).

[cr_{ct}] is a vector of n elements which corresponds to the nitrate concentration in recharge (kg/m^3) reaching groundwater.

Decision variables:

N_{ct} = fertilizer applied to the crop c in year t, kg/ha.

W_{ct} = water applied to crop c in year t (m^3).

Y_{ct} = production yield of crop c in year t, kg/ha.

L_{ct} = the nitrogen leached from each crop area (kg/ha) in year t.

Model:

Maximise $\sum_c \sum_t A_c(p_c Y_{ct} - p_n N_{ct} - p_w W_{ct})/(1+r)^t$, subject to:

$Y_{ct} = a + bW_{ct} + cW_{ct}^2 + dN_{ct} + eN_{ct}^2 + fW_{ct}N_{ct}$

$L_{ct} = g + hW_{ct} + iW_{ct}^2 + jN_{ct} + kN_{ct}^2 + lW_{ct}N_{ct}$

$cr_{ct} = L_{ct}/r_t$

$[\mathrm{RM}][cr_{ct}] \leq [q_{os}]$

The paper presents a way to apply the model to a small hypothetical catchment and the results for different scenarios. The scenarios were defined based on the initial conditions (initial nitrate concentration in the aquifer), length of the planning horizon (management period), recovery time (the time from when the concentration constraints are imposed), and policy options (whether the fertilizer application could vary over space and time). The results demonstrate that both the planning horizon and target recovery time strongly affect the optimal fertilizer application rates and the cost of achieving the environmental goals: it is more expensive to achieve the targets soon; and longer planning horizons result in greater pollution and more restrictions on fertilizer use. They also demonstrated that it is cost effective to allow variations in fertilizer usage over the planning horizon. Even though the irrigation water application was modelled as a variable, it was fixed in the demonstration.

The proposed approach combines the response matrix method with embedded formulations to describe the relationship between fertilizer application, leaching, and crop production. The embedded non-linear optimisation model was coded in GAMS and solved using the MINOS solver. The optimisation framework proposed by Peña-Haro et al. has a few interesting features. Perhaps they are the first to recognize the importance of considering the current nitrate status of the groundwater system, as well as the implications of the choices of management period length and target recovery time.

The model, however, can be non-convex and difficult to solve. Given that the recharge r_t is constant, the above formulation models a quadratically constrained quadratic programming problem (QCQP) which is generally non-convex (d'Aspremont & Boyd, 2003). The formulation can be re-arranged as follows.

Max $\begin{pmatrix} W_{ct} & N_{ct} \end{pmatrix}\begin{pmatrix} a_0 & b_0 \\ c_0 & d_0 \end{pmatrix}\begin{pmatrix} W_{ct} \\ N_{ct} \end{pmatrix} + \begin{pmatrix} e_0 & f_0 \end{pmatrix}\begin{pmatrix} W_{ct} \\ N_{ct} \end{pmatrix} + g_0$

Subject to $\begin{pmatrix} W_{ct} & N_{ct} \end{pmatrix}\begin{pmatrix} a_i & b_i \\ c_i & d_i \end{pmatrix}\begin{pmatrix} W_{ct} \\ N_{ct} \end{pmatrix} + \begin{pmatrix} e_i & f_i \end{pmatrix}\begin{pmatrix} W_{ct} \\ N_{ct} \end{pmatrix} + g_i \le 0$

If the matrices $\begin{pmatrix} a_0 & b_0 \\ c_0 & d_0 \end{pmatrix}$ and $\begin{pmatrix} a_i & b_i \\ c_i & d_i \end{pmatrix}$ for all i are positive semidefinite[4], then the problem is convex (d'Aspremont & Boyd, 2003). However, depending on the values of the coefficients, the matrices may not satisfy the above condition.

On the other hand, the model has limited applicability for catchments where nitrogen fertilizer is the only manageable source of nitrate. Other variables such as stocking density may be included in the leaching function, but several independent variables can make the leaching and cost functions non-convex (T. Ramilan, Scrimgeour, Levy, & Romera, 2007). Considering the recovery time as a management option is questionable because the consequences are sometimes irreversible.

3.5 Discussion

For the optimal control of water pollution, environmental authorities need knowledge on the relationships between the pollution sources and threatened water bodies. Such information is extremely important for nonpoint source pollution control. The common practice is to use hydro-geological simulations to provide insight into the underlying physical systems. The simulation-optimisation framework is widely used in non-market based mechanisms for water pollution control.

Different types of simulation and optimisation based methods have been proposed to date. The simulation-optimisation framework designed by Amalsri and Kaluarachchi (2005) for nonpoint sources is different from that of Morgan and Everett (2005). The former used a closely coupled simulation-optimisation approach which simulated each possible management alternative (at least for ANN calibration) to observe the

[4] A real-symmetric matrix $A_{n\times n}$ is positive semidefinite if $x^T Ax \ge 0$ for all $x \in R^{N\times 1}$(Meyer, 2000).

potential impacts, while the latter used simulations to generate a set of constant parameters which are then used in the mathematical program. Hence, the response matrix technique employed by Morgan and Everett used physical simulations on a one-off basis and the coupled approach of Amalsri and Kaluarachchi used physical simulations dynamically. Both approaches have costs and benefits.

The response matrix technique is based on the linear response superposition. To apply the response matrix method for the optimal control of nonpoint source nitrate pollution, we have to assume that nitrate loadings into an aquifer from distributed nonpoint sources have linear relationships with groundwater nitrate concentration. In essence, the groundwater recharge from each diffuse source should be constant. Since the concentration is calculated by dividing the mass flow rate by recharge rate, non-linearity appears if both mass flow rate and recharge are considered as variables. Recent research, for example Rao, Basu, Zanardo, Botter, and Rinaldo (2009) empirically demonstrates that the superposition is applicable for most groundwater nitrate control problems.

When the sources have non-linear effects on the receptors, the response matrix method is not applicable (mostly, point sources can have non-linear effects). However, it is possible to develop approximate non-linear mathematical models of the source-receptor relationships (Ejaz & Peralta, 1995). If the relationships are convex, for example, if quadratic functions are assumed, the optimisation models may be solved using available NLP techniques.

When the underlying physical system is so complicated that the source-receptor linkages are hard to model, the modellers are compelled to use coupled simulation-optimisation approaches such as Amalsri and Kaluarachchi's (2005) and search for an optimal solution. This is a time consuming and costly exercise, and the solution may be a near optimal rather than a unique global optimal.

On the other hand, linear responses to nitrate loading alone do not guarantee well behaved optimisation models. If management variables other than loading (fertilizer application rate, stocking rates, etc.) were to be controlled, non-convexities may still arise. Coupled approaches are useful when the adoptable management variables have non-convex relationships. However, our analysis does not recognize any good reason to prefer models that optimise such management variables over nitrate loading, mainly because of the availability of methods and tools to estimate loading from diverse agricultural practices.

The literature suggests that many water pollution control problems can be approximated to convex and solvable models. The research to date has addressed two possibilities of non-linearities in nonpoint source nitrate control models: non-linear responses of nitrate loading and management variables with non-linear behaviours. But non-convexities may arise from other causes, such as the discontinuities in the actual cost/benefit functions. For example, commercial farming may not be economically feasible without a minimum rate of fertilizer application or stocking, and thus without a minimum level of nitrate loading.

Due to the spatial and temporal effects of diffuse nitrate discharges, a mathematically optimal pollution control policy would impose non-uniform controls on spatially distributed sources. For example, a farm which is close to a threatened stream will face more stringent controls compared to other farms. When non-uniform controls are imposed, social resistance is inevitable. Hence, even though the regulator had perfect information on the physical and economic characteristics of the dischargers, and could come up with an optimal control policy, there are obstacles to implementing such a policy. Eventually, the world is moving towards market forces, away from the command-and-control policy for environmental protection.

Chapter 4

4 Pollution Permit Trading Systems[5]

4.1 Introduction

In this chapter, we review the state-of-the-art of water pollution permit trading systems which are also known as water quality trading systems. We first discuss the context of environmental pollution permits as a tradable commodity. We provide a brief introduction to the types of tradable pollution permits. Then we present the general theoretical literature on pollution permit trading systems. Next, we focus specifically on water pollution, and review the existing and proposed water pollution permit trading systems. We conclude with a summary of the lessons learned from forty years of research and experience in water pollution permit trading.

4.2 Pollution Permits as a Tradable Commodity

Natural resources such as water are usually considered as common pool, publicly owned, resources. But economists have long argued the need for transferable private property rights for environmental resources (Coase, 1960; Dales, 1968; Ellerman, 2005; Tietenberg, 2003). Still, there are conflicting views about private property rights to pollute the environment. One extreme is full property rights in perpetuity which

[5] Parts of this chapter were included in Prabodanie, Raffensperger, and Milke (2010) and Prabodanie and Raffensperger (2009b).

implies fully transferable explicit ownership. One familiar example for this type of tradable property rights is the New Zealand's fishing quota system (Newell, Sanchirico, & Kerr., 2002; Straker, Kerr, & Hendy, 2002) discussed below.

Ellerman (2005) made a strong claim in support of full (permanent) property rights. He compared the tradable permits for environmental goods with existing private property rights for land. Centuries ago, communities faced similar problems in allocating rights to land, another common pool resource. With rising scarcity, people devised institutions for allocation and pricing of land use rights. Today, all those centralized land allocation systems have failed and evolved to a system of full private property rights.

The environmental community at the other extreme stands by the position that environmental resources should be publicly owned, and hence, the government should take full control over the natural resources such as air and water. The middle ground is, as accepted by many economists and environmentalists, privatization of the rights to access the resource to a pre-specified degree (Tietenberg, 2003) rather than full privatization of the resource. Most emission permit trading systems in the United States fall into this category. The emission permits traded in the US, for example the sulphur dioxide emission permits discussed below, are clearly not permanent property rights, but rights to discharge pollutants at a defined rate for a defined time period (David, 2003; Tietenberg, 2003). Such temporary entitlements are better explained as property leases or rentals rather than property ownerships.

In conclusion, whether the environment should be publicly owned, privately owned, or rented on a short-term basis is an unresolved issue to date. The decision has economic, social, and political implications. Empirical evidence suggests that each approach works under the right circumstances (Burtraw, 2000; Environmental Protection Authority, 2003; Newell, et al., 2002; Tietenberg, 2003). Regardless of who owns the environmental resources, the market-based approaches can help improve the efficiency of resource allocation. Hence, the literature on pollution permit trading has made progress even though the right legal position of pollution rights between the extremes of private ownership and public ownership remains an open question.

4.2.1 Full Property Rights Example: New Zealand Fisheries ITQ System

A tradable fishing quota regime was introduced in New Zealand when the government passed the Fisheries Amendment Act in 1987 (Straker, et al., 2002). New Zealand's fisheries quotas are known as the Individual Transferable Quotas (ITQs). ITQs are specified separately for each quota management region and fish species as a fraction of the Total Allowable Catch (TAQ), the maximum amount of fish that can be harvested. Fishing quotas were initially allocated (for free) among the regional fishing entities, based on the historic catch levels. Every year, the fisheries regulator (Ministry of Fisheries) determines the Total Allowable Catch for each quota management region and fish species, taking into account current population, regeneration rates, and environmental values which vary across regions, fish species, and time. TAQ effectively determines the maximum amount of annual catch allowed by the quotas held. Because the fisheries contain multiple species, the fishermen usually cannot catch one species without incidentally catching others, and therefore they have to rebalance their species portfolio during each year.

New Zealand's fishing quotas are permanent property rights. They can be bought, sold, leased (in or out), or used (fished). Since 1986, New Zealand ITQ markets have recorded active trading, and overall, the tradable permit policy has been a success (Newell, Papps, & Sanchirico, 2005; Newell, et al., 2002). In 2000, New Zealand had 275 fishing quota markets. As at 2000, about 140,000 quota leases and 23,000 quota sales have occurred. Interestingly, from 1986 to 2000, the annual number of leases has increased 10 fold and the annual number of quota sales has dropped significantly from 3200 sales to about 1000 sales.

4.2.2 Property Rental Example: United States Sulphur Dioxide Trading System

The US sulphur dioxide (SO_2) trading program is considered as the most successful tradable permit program in achieving the environmental goals at least cost (Burtraw, 2000; Schary & Fisher-Vanden, 2004). Unlike New Zealand's ITQs, the US sulphur dioxide allowances are defined for a specific calendar year. Each allowance authorizes the allowance holder to emit one ton of sulphur dioxide. If an allowance has not been used in the specified year, it can be carried forward to future years. The allowances are fully transferable between sources and other parties who wish to buy and retire the permits for the sake of the environment.

For every year, the total aggregate emission level (cap) is defined by the government authorities. The cap is initially allocated among the sources for free based on an allocation formula (a small percentage of the total, less than 3% is withheld and auctioned). The sources are required to install continuous emission monitors and reporting software, so that quarterly electronic reports are submitted to the USEPA emission tracking system electronically. The emissions and allowance holdings are balanced at the end of the year. The sources whose total annual emissions exceed the allowance holdings are charged a penalty and required to surrender allowances in the next year to match the deficit. Those who performed better can carry the surplus to the next year. Regardless of how many allowances a source has acquired during a year, the annual emissions should still meet the federal sulphur dioxide emission standards. Therefore, the limit that applies on each source is either the allowance holding or the federal standard, whichever is more stringent.

The success of the program is well evidenced. According to Burtraw (2000), the program has achieved 100% environmental compliance and the economic benefits are substantially above the cost of the program. According to Schary & Fisher-Vanden (2004), two factors contributed to the success of the program: (1) the creation of a common standardized commodity which is capable of achieving the environmental goals and (2) the design of the program to attractively and efficiently facilitate and encourage trading.

4.2.3 Full Privatization vs Rentals

Under full privatization, the government loses control of the natural resources and may have to buy back for conservation. For example, in the early movement from regulation to privatization, the New Zealand government allocated fishing rights as fixed tonnages based on past history. Later, the government found that the total allocations exceeded the sustainable yield in some fisheries and had to buy back (Newell, et al., 2002). This happened because of the allocation of fixed quantity rights in a situation where the total quantity available was uncertain. If the private property rights are specified as a fraction of the total available (as in the current New Zealand ITQ system), the government can still control resource consumption by setting the total allocation to maintain sustainability. On the other hand, full privatization provides full flexibility to the users because it allows free asset markets and asset-lease markets. Potential for market monopolies, barriers to new-comers, and fairness issues are some complaints about full private property rights for natural resources.

If the government rents the rights to use the natural resources (or to pollute the environment) for fixed short periods, it still has a significant level of control. For example, the US sulphur dioxide allowances provide "adequate, as opposed to complete, security to the permit holders while keeping the ability to adopt more stringent standards if required" (Tietenberg, 2003). So while the full property rights for the environment provide full flexibility to the users, government controlled resource rental systems can provide adequate security to both the users and the environment.

4.3 Types of Tradable Pollution Permits

The literature on air and water pollution permit trading discusses two general types of tradable pollution permits: emission permits and ambient permits (McGartland, 1988; Montgomery, 1972). Ambient permits, sometimes referred as pollution permits[6], are defined based on the receptor. Emission permits are defined based on the source.

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[6] To describe the different types of permits, we use the terminology commonly found in the literature. However, Montgomery (1972) used the term "pollution permits" to describe ambient permits. Since the nineteen seventies, the authors have used the terms "ambient permits" and "emission permits" as standard terms in both theoretical and empirical literature published on pollution permit trading systems.

4.3.1 Ambient (Receptor) Permits

An ambient permit is a right to increase the pollution level at a specific receptor. Ambient permits are issued separately for each receptor. They allow the permit holder to discharge so that the pollution effect at any receptor does not exceed the specified limit. Since a pollution source generally affects a number of receptors, a source has to assemble a portfolio of permits to match the impacts on all receptors. When there are multiple receptors, a separate market is created for each receptor, but in every market, permits are freely tradable on a one-to-one basis.

Ambient permits may be specified quantitatively as the permitted increase in pollution or as a proportion of the total allowed pollution at the receptor. For example, a point source discharger may be given a permit to discharge 50 kg of nitrate into a stream segment, or a permit for 20% of the total allowed nitrate discharge into a stream segment. Proportionally defined ambient permits provide more flexibility in attaining environmental goals because the ability (capacity) of the environment to accept and dilute pollutants varies over time, and the discharge levels can be adjusted relative to the updated maximum acceptable pollution levels.

The major problem with ambient-type pollution permits is the inevitable confusion for the users in assembling the right portfolio of permits to cover the operations in each period. The sources incur high transaction costs in purchasing a portfolio of permits.

4.3.2 Emission (Source) Permits

An emission permit allows the permit holder to discharge a pollutant at a specified rate. Theoretically, an emission permit is equivalent to a bundle of ambient permits. As the sources and receptors are spatially distributed, the emission permits held at distinct sources have dissimilar pollution impacts on the receptors. Transfer of emission permits among sources can change the level of pollution at a receptor positively or negatively. Therefore, emission permits cannot be freely traded one-to-one as ambient permits. Some trading rules are required to support trade in emission permits. Different trading rules have been used and different types of emission trading systems have evolved as a consequence. The most commonly found emission permit trading systems are trading ratio systems, zonal permit systems, and pollution offset systems. Trading ratio systems allow bilateral trade based on pre-determined quantity adjustment ratios, zonal permit systems categorise sources with similar spatial impacts into zones and allow one-to-one trade within zones, and pollution offset systems use environmental simulations to validate trades.

From a user’s point of view, emission permits are easy to understand and adhere to, because unlike ambient permits, emission permits directly specify the permitted discharge levels. With emission permits, the cost of setting trading rules raises the cost of market design. Validating and authorizing trades according to the pre-determined rules may increase transaction costs.

4.4 Pollution Permit Trading Systems: General Models

Early theoretical literature on permit trading covers both air and water pollution in general and the later studies have been specialized to specific resources: water, air, or land. In this section, we discuss the general approaches proposed in the early literature.

4.4.1 Ambient Permit Trading Systems

Ambient permits are similar to any other freely tradable commodity. Once the permits are defined and initially allocated, an ambient permit trading system would operate as a “free” market (McGartland, 1988). Montgomery (1972) was the first to mathematically prove that a market in ambient permits would lead to efficient allocation of pollution abatement responsibilities. He proved the existence of a market equilibrium in ambient permits which coincides with the allocation of abatement responsibilities which meets the environmental quality standards at least cost to society.

Under an ambient permit trading system, the pollution sources have to trade in many markets to assemble a portfolio of permits, and this raises the transaction costs. Hence, ambient permit systems are most suitable when very few receptors are involved and the pollution sources have quick responses, so that only one or few environmental constraints are involved.

To avoid having to purchase a permit portfolio, Atkinson and Tietenberg (1982) proposed a highest ambient permit system, which approximates the multiple receptor situation to a single receptor situation. When multiple receptors are present, they proposed to create a single ambient permit market for the most polluted (worst) receptor. Using a case study, Atkinson & Tietenberg showed that the proposed highest ambient permit system is much simpler, even though the cost is slightly higher compared to the ambient permit system.

4.4.2 Trading Ratio Systems

Montgomery (1972), who laid the theoretical foundation for pollution permit trading, discussed tradable emission permits also. The emission trading system discussed by Montgomery was actually a trading ratio system, even though he described the trading ratio mechanism as a "rule governing exchange of emission rights". The rule was explained as follows: a buyer may emit up to a level which causes pollution not more than that which would have been caused if the seller had emitted to the maximum level allowed by the permit. If source i buys an emission permit of size e_k from source k, source i can emit up to a level e_i so that $h_{ij}e_i \leq h_{kj}e_k$ for all j where h_{ij} and h_{kj} are the "transport coefficients" which relate the sources and receptors (similar to the response coefficients discussed in the previous chapter, ignoring the timing of effects). Thus the trading ratio applies to source i for the purchases from source $k = \min_j (h_{kj}/h_{ij})$. This was a non-degradation trading ratio which prevents any additional pollution as a result of trade, and there are other ways of selecting trading ratios, for example, Hung and Shaw (2005) discussed in section 4.5.1.

Montgomery (1972) proved theoretically that a market in emission permits also leads to efficient allocation of abatement responsibilities. But according to his analysis, a market equilibrium of emission permits is efficient only if the initial allocation of emission permits meets quality standards at all the receptors with equality (i.e., if the initial allocation of emission permits bind all the receptors). He admitted that such an initial allocation of emission permits might not exist.

Generally, trading ratio systems allow bilateral trades based on pre-determined trading ratios. For example, a nitrate emission trading ratio of 5:1 for the sources A and B means, A has to buy a 5 kg permit from B to increase his or her emission by 1 kg. Trading ratio systems suffer from the free-rider problem and thin trading. The free-rider problem arises when some polluters benefit from the transactions of others (McGartland, 1988). For example, assume that polluters A, B, and C affect receptors R1 and R2 by the transport coefficients shown in Table 3.1. If B wishes to buy from A, a non-degradation trading ratio would be 5:1. Assume that B buys a 5 kg emission permit from A and discharges only 1 kg as allowed. This trade would decrease concentration at receptor R2 by $3\times5-1\times1 = 14$ mg/l, and source C would gain a free ride to increase its emission.

	A	B	C
R1	1	5	0
R2	3	1	2

Table 3.1: Transport coefficients (mg/l) for sources A, B, and C and receptors R1 and R2.

If the trading ratios were selected on a non-degradation basis, the high purchase cost increases the overall cost and discourages participation. Downward adjustments of trading ratios to increase cost efficiency would violate water quality standards at some receptors. Regardless of the way the trading ratios are selected, under such pair-wise or bilateral trading systems, those who are willing to buy or sell have to find trading partners, and the search is a costly affair.

4.4.3 Pollution Offset Systems

Krupnick, Oates, & Verg (1983) proposed the “pollution offset system” as a solution to the high transaction costs associated with the many markets created by Montgomery’s ambient permit system. With the pollution offset system, emission sources are free to trade as long as the environmental quality standards are not violated at any receptor. This system needs an environmental quality model to simulate the impact of each proposed transaction and ensure that it does not violate quality standards at any receptor. Krupnick et al. showed that if all gains from trade are exhausted, then the outcome is a least cost solution to the society’s problem.

McGartland and Oates (1985) presented the "modified offset system", introducing redefined quality standards to the original offset system designed by Krupnik et al. (1983). Standards were redefined so that, for every receptor, the environmental quality standard is equal to the predetermined standard or the current (initial) level of environmental quality, whichever means less pollution. The system was explained as follows.

The vector of redefined quality standards, $Q^{**} = \min(Q^0, Q^*)$ where Q^* is the vector of predetermined quality standards and Q^0 is the vector of current quality levels. With redefined standards, it is always possible to find an E^0 such that $E^0H = Q^{**}$ where E^0 is the vector of emissions implied by the initial allocation of permits, and H is the matrix of transport coefficients. This is the condition under which the market equilibrium in emission permits solves the cost minimization problem (Montgomery, 1972). On the above premise, McGartland and Oates showed that their system is mathematically identical to Montgomery's ambient permit system, Montgomery's proofs are applicable to the modified pollution offset system, and thus it leads to efficient allocation of emission permits.

Regardless of how the quality standards are defined, offset-based trading systems need environmental simulations to validate every transaction, and the simulations increase the overall transaction cost. Offset based trading systems also have the free-rider problem. For example, assume that polluter A affects receptor R1, B affects receptor R2, and C affects both receptors R1 and R2. The relevant transport coefficients are as shown in Table 3.2. If C sells to A, B gains a free chance to increase pollution at receptor R2.

	A	B	C
R1	1	0	1
R2	0	1	1

Table 3.2: Transport coefficients (mg/l) for sources A, B, and C and receptors R1 and R2.

Thin trading is another criticism of offset-based bilateral trading systems. A proposed pair-wise transaction may be infeasible if a quality standard at any receptor is violated. In the above example (if only A, B, and C are in the region) C can sell to A or B, but any purchase by C and any trades between A and B are all infeasible.

McGartland (1988) discussed the transaction costs and free rider problems associated with ambient permit systems and offset systems. He argued that the polluter's problem in both the ambient permit system and pollution offset system are mathematically equivalent under perfect competition, a competitive equilibrium exists, but there are many obstacles in reaching this least cost equilibrium. He mentioned that brokers can help overcome these obstacles.

4.4.4 Centrally Controlled, Multilateral Permit Trading

McGartland (1988) identified the difficulties in attaining the least cost distribution of permits via trading, but he did not propose a complete solution. More than a decade later, Ermoliev, Michalevich, and Nentjes (2000) discussed how a permit market can be practically designed so that it is capable of achieving efficient permit allocations.

Ermoliev et al. (2000) proved that bilateral sequential trades converge to cost efficient emissions only in the case of a single receptor (one constraint on total emission). In the case of many receptors, sources generally cannot increase their emissions without negotiating with several other sources, and multilateral emission permit trade is required. They presented a Multi-Agent Decentralized Market (MADIC) which requires an intermediate agency, a "broker," who coordinates multilateral trade, acting like a Walrasian auctioneer. The system was explained as follows.

The sources and agency are connected through a computer network. The agency stores information such as the transport matrix, the environmental standards, and the current quality levels. The agency sets preliminary ambient prices[7] and translates them into emission prices for each source using the transport matrix. Once the sources receive the proposed emission prices, they determine their individual demands or supplies and

[7] An ambient price is a price for increasing pollution at a receptor.

send the information to the agency. The agency adjusts the prices based on excess demand or supply, retransmits the new prices, and continues this process until equilibrium is achieved. Ermoliev et al. proved that this method leads to efficient allocation of permits, regardless of whether the permits are defined as ambient permits or emission permits. Proofs were given for emission permits which can be mapped into sets of ambient permits.

Compared to conventional bilateral trading systems, the proposed centrally-controlled market reduces transaction costs because the traders buy and sell from the auction without having to find a trading partner. Multilateral trading increases the opportunities for trade in emission, because a polluter who has impacts on many receptors can buy from multiple sellers to offset the effects. For example, if there were a MADIC system for the case given in Table 3.2, polluter C would buy simultaneously from polluters A and B. However, the main problem of such a centrally controlled auction is that equilibrium may not be achieved quickly or monotonically. Ermoliev et al. (2000) mentioned that convergence to equilibrium may take a long time.

4.5 Water Pollution Trading Systems

Dales (1968) was the first to demonstrate the applicability of market solutions to the problem of water pollution. He recommended a property rights rental system for water pollution, but admitted that the task is not as easy as with land. Dales suggested that the government must make sure that a sustainable amount of pollution rights is issued and some of the allowable rights are reserved as a means of altering the total supply. He claimed that this pollution rights market is not a true market, as even if a hike in price indicates an increase in waste disposal value, the government cannot increase the allowable waste discharge capacity in response.

Water pollution permit markets, in operation or as proposed, vary in the scope of application, pollutants traded, and the program design. The scope of application varies from point source trading systems at the river level to integrated point and nonpoint source trading systems at the catchment scale.

Most of the earliest markets were to trade biochemical oxygen demand (BOD) in rivers. BOD measures the amount of oxygen required to decay the organic compounds in a litre of water. BOD is an overall measure of water quality, because many pollutants such as nitrogen, phosphorus, and organic matter increase BOD level. Later, tradable permit programs have been proposed for critical water pollutants such as nitrate and phosphorus.

The designs of water pollution permit trading systems vary by the rules and procedures that govern trade. Woodward, Kaiser, and Wicks (2002) discussed four commonly found market structures of water pollution permit markets in the US: exchanges, bilateral negotiations, clearinghouses, and sole source offsets. This was a general categorization, and market design is more than just the choice between bilateral trading and trading in exchange. It is difficult to categorize the water pollution permit trading systems based on the market design, because a wide variety of design options has been proposed. Hence, the water pollution trading systems discussed in the following section are categorized based on the scope of application rather than the market structure.

4.6 Point Source (PS) Trading Systems

The literature on trading water pollution permits is dominated by point source trading systems. The obvious reason is that point sources are easy to measure and control compared to nonpoint sources. They are usually designed at the river level and applicable to a variety of surface water pollutants. The simplest way for PS trading is the cap-and-trade mechanism successfully adopted in air pollution trading programs. Cap-and-trade programs are simple and easy to understand; a cap on total pollutant load (usually on annual load) is determined; the cap is distributed among the sources; and free one-to-one trading is allowed (Environomics, 1999; King & Kuch, 2003; US EPA, 2007). However the simple cap-and-trade mechanism is not always suitable for PS trading, mainly due to the locational effects of PS emissions. Therefore, the trading systems are usually designed to account for the variations in effects caused by the discharge point. We discuss a few interesting attempts to protect river water quality through PS water pollution permit trading systems, both theoretical and practical.

4.6.1 Early Work

The Fox River in Wisconsin was the first body of water in the United States for which transferable discharge permits were allowed (O'Neil, David, Moore, & Joeres, 1983). The pollutant traded was BOD. The Fox River trading system was a highly restricted trading system. Trade was allowed only if the permitted discharge levels could not be met by adopting technological standards, and if the buyer and the seller were on the same river segment; hence only one trade has ever taken place.

Despite the actual market regulations, O'Neil et al. evaluated a non-degradation based trading ratio system for the Fox River. The market was modelled for two receptors. They used a one-dimensional quality model (Qual-III) of the river to calculate the transport coefficients for varying river conditions of temperature and flow. They estimated bilateral trading ratios from transport coefficients, using Montgomery's method, so that water quality standards were met at all receptors, under any flow and temperature condition. They showed that tradable pollution permits are cost effective (compared to the command-and-control approach) and capable of maintaining water quality standards, even when the river conditions are uncertain and dischargers have different effects on river water quality.

Eheart, Brill, Lence, Kilgore, and Uber (1987) emphasised the usefulness of tradable discharge permit systems in maintaining water quality standards under stochastic river conditions (varying assimilative capacity). Eheart et al. simulated a hypothetical trading system of dynamic emission permits for biochemical oxygen demand control in the Willamette River in Oregon, United States. Dynamic discharge permits allow the emission levels to be adjusted according to the temporal variations in the assimilative capacity of the receiving water body. In contrast, the conventional static discharge permits specify a fixed allowable discharge level. According to Eheart et al., dynamic permits may be defined as periodic permits or conditional permits. With periodic permits, allowable discharge is given as a function of the calendar date. The simplest is the two period permit system, the critical or drought period and the non-critical or wet period. With conditional permits allowable discharge is given as a function of river conditions.

The market was simulated using a linear program. For comparison purposes, programs of non-tradable dynamic permits, tradable static permits, and non-tradable static permits were simulated. One important finding of this study is that dynamic permits, whether transferable or not, are more efficient in terms of both cost and quality, because the discharge levels are dynamically determined based on the river conditions. If the permits are tradable, further cost savings may be accrued. The interesting concept in this work is the effectiveness of dynamic permits (similar to proportionally defined ambient permits) compared to the static (fixed quantity) permits.

Leston (1992) performed a study of a two-pollutant, two-season pollution offset system for the Colorado River of Texas, United States. The two pollutants considered were biochemical oxygen demand and ammonia nitrogen. Both pollutants influence the dissolved oxygen level of a stream, hence a pollution offset by the other pollutant was allowed, and only the dissolved oxygen level was constrained as a quality requirement. Leston's study indicated significant cost savings from pollution offset systems. According to Leston, pollution offsets from the two different pollutants contributed to almost all the savings, and the seasonal variation of permit design had little effect on cost savings. Leston's results indicate the usefulness of the offset mechanism in trading different pollutants which affect the same environmental constraints.

4.6.2 Theoretical Extensions

Weber (2001) modelled a theoretical trading system to allocate surface water use rights and emission rights along a river. She argued that the combined effects of water withdrawals and emissions must be considered in allocating surface water use and pollution rights. For the modelling and analysis, users (diversion points) were indexed according to the location along the river, in the order of increasing distance from the origin. The level of benefit derived by every user was considered as a function of the quality and the quantity of water available at the point of diversion, quantity consumed, and amount of effluent discharged. The optimal allocation problem was modelled with two types of environmental constraints: minimum levels of quality and quantity of water required at each diversion point and at the end point (after the last user). In-out balance equations were specified for water quantity and quality at each diversion point.

Weber modelled the optimal allocation of water use and discharge rights and the market equilibrium in permits for water and pollution damages (ambient type permits) to prove that the market equilibrium implements the optimal allocation. She analysed the locational prices (obtained from the shadow prices of the balance equations) and showed that the prices decline from upstream to downstream. Weber's results indicate the efficiency gains of a combined market in surface water use and point source discharge rights, but the results may not apply to groundwater rights and nonpoint source discharge rights. Also, the user's benefit function discussed in Weber's theoretical model would be hard to estimate in practice.

Hung & Shaw (2005) presented a new type of trading ratio system for trading point source emission rights based on the unidirectional flow of water in rivers. In the proposed system, an environmental authority first sets environmental load standards for every discharge location (zone) along the river. Then the effluent cap at each location is set sequentially, starting from upstream, so that the cap equals the location's load standard minus the effluent load transferred from upstream. Obviously setting uniform standards along the river is unfair to the downstream dischargers, and the upstream standards should be tighter than the downstream caps. The cap is distributed among individual dischargers in the zone as the initial allocation so that the cap at every discharge location is binding. The trading ratios among sites are set equal to the relevant transport coefficients. Dischargers are allowed to trade with each other freely based on trading ratios. If a discharger j buys X units from an upstream discharger i, the cap at the buyer's location would be relaxed by $h_{ij}X$, allowing the buyer to discharge more $h_{ij}X$ units. A purchase from downstream would not allow an upstream buyer to increase the discharge, and hence a rational discharger would not buy from downstream.

Hung and Shaw proved that this trading ratio system leads to efficient allocation of emission rights under both simultaneous trading and sequential bilateral trading. As they argued, the transaction costs are lower because the trading rules are simple, permit portfolios are not required, and either a centralised double auction or bilateral trading is possible with this type of emission permits. Hot spots can be avoided by having caps at each discharge location. The free rider problem is avoided because the zonal caps are fully allocated; any additional increase in discharge should come with more permit purchases. The environmental constraints are binding ex-ante and ex-post ensuring full capacity utilization. However, this is a very specific trading system suitable for point sources located along a river. Market competitiveness may be affected by the load standards and the caps, endogenously specified for every discharge location.

4.6.3 Practical Approaches

The Hunter River Salinity Trading Scheme in Australia (Environmental Protection Authority, 2003) is a good example of a real world trading system which succeeded in improving surface water quality. In this trading system, the river is divided into river blocks (zones), based on how many days the block will take to pass Singleton, a downstream location. Each point source located along the river belongs to one block.

The Hunter River Scheme operates in real time. The scheme operators (representatives of the New South Wales government) continuously monitor the river flow and salinity levels and determine how much more salt can be discharged into each block so that river water quality standards are not violated.

Emission permits are defined, not quantitatively, but as a percentage of the total allowed discharge. Initially, a total of 1000 discharge credits were allocated among the users. Credit holders can discharge salt into their river blocks only in proportion to the credits held; if a user has 30 credits, he or she can discharge only 3% of the total amount of salt allowed for the particular river block. Both intra and inter block trade is possible on a one-to-one (quantity) basis. Trades within a block require the buyer and seller to act accordingly on the same day, and trades between two blocks require the buyer and seller to act accordingly on different days.

For example, if source *A* in the 160-day block sells 20 credits to source *B* in the same 160-day block today, then *A* has to reduce discharge by 2% of the total allowed in his block today and *B* can increase the discharge by 2% of the total allowed in the same block today. If *A* sells 90 credits to source *C* in the 155-day block (downstream) today, *A* has to reduce discharge by 9% of the total allowed in his block today, and *B* can increase the discharge by 9% of the total allowed in his block five days later (the 160-day river block today becomes the 155-day river block five days later). This trading scheme allows trade across time.

The prices are negotiated. A clever player would buy and sell based on river flow forecasts, because if the flow is high, the river can dilute more salt, and the total allowable discharge would be greater.

An initial allocation of credits was made free at the commencement of the Hunter River Scheme in 2002, and 200 credits expire every two years from the commencement. New credits are sold in public auction so that the total number of credits is limited to 1000. All sold permits expire in 10 years. So there will be an auction for 10 year permits at 2 year intervals from the implementation of the project.

The interesting feature of this schema is that it creates two markets, one in long term pollution rights (10 years) and another in short-term leases (one day). Therefore, the Hunter River trading schema is similar to the New Zealand Fisheries ITQ system, with some variations, mainly the time scales. However, the same structure can be adopted with different (possibly longer) time scales and may be applied to other pollutants and nonpoint sources.

The US has implemented many point source water pollution permit trading systems (Environomics, 1999; King & Kuch, 2003; US EPA, 2007), but the results are not impressive. Most of these trading programs are simple cap-and-trade systems or bilateral trading ratio systems. These trading programs allow trade in a variety of pollutants such as nitrogen, phosphorus, selenium, temperature, mercury, and ammonia. Different criteria such as non-degradation, pollution offsetting, and regional basis, have been adopted to determine the bilateral trading ratios. Since many of the US point source trading systems are for trading nutrients, we discuss them in section

4.9. More details on US water quality trading systems are available in US EPA (2007) and Environomics (1999).

4.6.4 Conclusions on Point Source Trading

Our literature review provides evidence that the existing and proposed point source water pollution trading systems are capable of attaining the intended goals. All the relevant issues are discussed in the literature, and both simplified and detailed trading systems have been proposed. The best fit trading schema should be selected depending on the availability of required information, level of certainty in the information, and the level of flexibility allowed in expected outcomes. For example, if water quality standards for some pollutant are to be met on a daily basis, if only point sources are present, and if continuous monitoring and control is possible, a trading structure like the Hunter River Scheme is a good solution. On the other hand, if the water quality goals can be achieved via an annual cap on total pollutant load and if a higher level of accuracy is not expected in the outcomes, a simple cap-and-trade mechanism would be sufficient.

A better way for cap-based trading is proposed in dos Santos (2009). He proposes an auction mechanism which uses a mathematical programming model to find efficient market prices relative to bids submitted by the users. A hydro-electric generator which acts as the auctioneer receives the revenue from permit sales in exchange for guaranteeing minimum flow levels required to dilute the pollutants. It also takes into account the non-linear behaviour of pollutant transport in river systems. The auction is designed to price the permits taking into account the competing commercial interests of different parties involved, and thus provides innovation for better design of cap-and-trade systems.

The above discussed PS trading systems are not directly applicable to nonpoint sources for two main reasons. First, pollutant transport in groundwater is much more complicated than in surface water bodies, mainly because surface water flow is fast and uni-directional while groundwater flow is slow and dispersive. Second, PS water pollution trading systems are designed for the short term and nonpoint sources have long term impacts. The main focus of this thesis is therefore nonpoint sources.

4.7 Nonpoint Source (NPS) Water Pollution Trading Systems

Most NPS water pollution permit trading systems have been designed for nutrients, because nutrients such as nitrogen and phosphorus are the most critical NPS water pollutants. They are usually known as NPS nutrient trading systems.

NPS nutrient trading is complicated due to the difficulties in measurement and control and the complex hydro-geological processes that affect the fate and transport of NPS emissions. O'Shea (2002) highlighted that markets for diffuse sources need the close cooperation of scientists and economists. She suggested that the "task for scientists is to improve the knowledge of the linkage between emissions at source and their presence within a receptor so that economists can develop their models accordingly."

Theoretical designs of NPS nutrient trading systems are rare in the literature. One reason may be that the institutional structure in the US, the country which has pioneered the tradable rights approach for the environment, does not support water pollution permit trades between nonpoint sources. We discuss and review two theoretical NPS nutrient trading systems proposed to date: an ambient permit system and a zonal permit system.

According to our literature survey, Morgan, Coggins, and Eidman (2000) were the first to suggest a complete methodology for trading nonpoint source discharge permits. They discussed an ambient permit system for controlling nitrate concentration in a single targeted groundwater well (a single receptor). Their trading system consists of three sub models: (1) a production model which estimates the profits from different production practices (crop rotation and nitrogen fertilizer application rate), (2) a soil model which estimates the water and nitrate leaching from each production practice, and (3) a groundwater model which simulates the nitrate movement in groundwater. They assumed that one practice is continued during the planning horizon. Each permit was defined as a right to cause a certain level of concentration at the receptor in the last year of simulation. A centralized auction market was designed to operate as described below.

1. First, the auctioneer posts a price.

2. Farms submit the optimal production practice and the number of permits to trade (buy or sell) based on the posted price. Each farm knows the impact of each production practice on the concentration at the receptor.
3. The auctioneer runs the soil model and groundwater model with submitted production practices and checks whether the water quality standards are met all the time.
4. If standards are met, the auctioneer checks whether demand and supply match.
5. If both requirements are met, the price is finalised.
6. Otherwise a different price is posted accordingly.

Morgan et al. designed this trading system specifically for nitrate discharge permits, but it is equivalent to the general emission trading system proposed by Ermoliev (2000). Both are centrally controlled multilateral trading systems in which the traders and the auctioneer are connected through electronic media.

Morgan et al. assumed that each proposed production practice is continued throughout the planning horizon, meaning long-term permits. The system is acceptable only if the planning horizon is long enough, so that, for any combination of production practices, an equilibrium concentration is observed at the well by the end of the planning horizon. Otherwise, the system is unable to maintain the water quality standards all the time.

Even if the planning horizon was selected cleverly, nitrates already in the aquifer may cause the concentration to peak at some time before the end of the planning horizon. Then the simulations would suggest that the water quality standards are violated at some time, and the auctioneer would post a higher price while there was an excess supply of permits in the market (because the permits are defined based on the end of planning horizon constraint). For example, assume that the planning horizon was 60 years, and the water quality standard was 50 ppm for every year. For a set of production practices and buy bids, the simulated concentrations were 55 ppm in year 20 and 30 ppm in year 60. The auctioneer will post a higher price while there are excess permits available (50 ppm is available and only 30 ppm is allocated), and the iterations would not converge to an equilibrium. Hence, even for a single receptor, a large number of auction rounds may be needed to clear the market.

Kerr, Rutherford and Lock (2007) and Lock and Kerr (2008) proposed a NPS nutrient discharge permit trading system for the Lake Rotorua catchment in New Zealand. The primary purpose of this trading system is to control the nutrient input into the lake from the catchment land uses. This is a zonal trading system. Zones are specified based on the time lag in years between loading in the zone and discharge to the lake. Each nonpoint source (farm land) was assigned to one of the zones assuming that all nutrients from that farm land reach the lake at the same time (i.e., in one year). Permits were defined separately for each year, specifying the nutrient mass that the permit holder is allowed to discharge into the lake in the particular year (for example, 2010-permits, 2011-permits,…, 2200-permits). Loading from a farm in a T-years lag zone reaches the lake after T years, therefore, the farm owner must buy $T + t$ year permits to match the loading in year t. Temporal nutrient discharge targets (discharge goals for each year from the current date) have been set. The lake nutrient target for each discharge year determines the total available number of permits.

This system creates several markets for different permit types. They have proposed to combine lag zones (three or five) together to create a single combined market, but there will still be many combined markets because the maximum time lag can be 200 years. One-to-one bilateral trade is possible for each type of permit within and between zones. However, trades within a zone require the buyer and seller to act accordingly in the same year, while trades between two zones require the buyer and seller to act accordingly in different years. Hence, as the Hunter River Salinity Trading Scheme, this system also facilitates trade across time.

Among the NPS nutrients trading programs proposed to date, we find Lock and Kerr as the best compromise system in terms of maintaining the simplicity of the program while sufficiently addressing the spatial and temporal aspects of nonpoint source pollution. However, a few issues are present, leaving space for further development.

First, this zonal permit system is applicable only to a single receptor situation. Second, it assigns each farm to a single lag year or a block of a few lag years, and requires the farm to buy a single permit for the particular year or block. The nutrients, for example nitrates, loaded into an aquifer from diffuse sources do not usually reach a receiving water body at once, but gradually over a relatively long period. Therefore, we cannot assign every farm to one specific lag zone. Third, the quantity transported to the receiving water body may be less than the quantity loaded from the source, and the amount of attenuation varies depending on the location of the source and the hydro-geological properties of the flow paths. A trading system should take into account the varying levels of attenuation from farms.

4.8 Point-Nonpoint Source (PS-NPS) Water Pollution Trading Systems

States and environmental institutions all over the world have recognized the need for PS-NPS water pollution permit trading systems (Crutchfield, Letson, & Malik, 1994 ; Faeth, 2000; Fang, et al., 2005; David Leston, 1992; Ribaudo, et al., 1999), especially for controlling nutrients pollution. But the world lacks experience with such trading systems. One important factor that has driven the demand for such trading systems is the nutrient overload in surface water bodies jointly caused by point and nonpoint sources. The US nutrient trading programs which allow point sources to buy from upstream nonpoint sources are usually categorized and called PS-NPS nutrient trading systems, but as discussed in section 4.9 below, they are not true PS-NPS trading programs.

On the other hand, PS-NPS trading is not always required or feasible (David Leston, 1992; Ribaudo, et al., 1999). Ribaudo et al. (1999) argued that PS-NPS trading is most suitable when both point and nonpoint sources contribute significantly to the total pollutant load. If the contribution from either source category is extremely large relative to the other, the cost savings from PS-NPS trading may not justify the cost of designing and implementing a PS-NPS trading program. According to Leston (1992), for point and nonpoint source trading to be useful (in the US context), two conditions must be satisfied. First, nonpoint source control should be a more economical way of achieving water quality goals than further point source abatements. Second, the cost of measuring and controlling nonpoint source loadings and the uncertainty in loading estimates should not overwhelm the potential savings.

In this section, we discuss just one theoretical design of a PS-NPS water pollution trading system. A few others are discussed under section 4.9, nutrient trading systems in the US.

Horan, Shortle, Abler, and Ribaudo (2001) designed two types of trading systems to facilitate trading among and between point and nonpoint sources, distinguished by the way the NPS permits are defined. The first type allowed trading PS emissions and NPS loadings (emissions-to-expected loadings). The second type allowed trading PS emissions for diffuse source inputs, fertilizer and land (emissions-to-inputs). Both systems allow bilateral permit trades on a one-to-one basis within source categories, and using trading ratios between source categories. They derived expressions to calculate the trading ratios so that the total cost of pollution control is minimised. A single trading ratio was used in all trades between point and nonpoint sources.

Horan, Shortle, Abler, and Ribaudo (2002) applied their prior theoretical work for nitrogen trading in the Pennsylvania portion of the Susquehanna River basin (SRB) in the United Sates. Nonpoint source pollution control cost was considered as a function of nitrogen loading or input use. Point source abatement cost was considered as a function of emissions. The proportion of nitrogen delivered to Chesapeake Bay from the basin was calculated using predetermined delivery coefficients. The economic cost of pollution was considered as a function of nitrogen delivered to the Bay. The outcomes of the system were evaluated using simulation experiments. According to the observed results, the trading system in which NPS permits were defined in terms of nitrogen loading was more efficient than the trading system in which permits were defined based on inputs; the type of input permits affects the performance of input based trading systems; and a trading system with land permits performs less efficiently than a trading system with fertilizer permits.

The major problem with the above trading system and many other point and nonpoint source trading systems in the US is having a single trading ratio which applies for all trades between point and nonpoint sources. The quantity of nitrogen transported to a water body from spatially distributed nonpoint sources may differ from source to source, and different trading ratios are needed for different pairs of sources.

4.9 Nutrient Trading Systems in the United States

The United States is the only country which has many active water quality trading programs. Water quality trading, and thus nutrient trading, in the US is governed by the Clean Water Act of 1972 (US EPA, 2007). The main focus of the Clean Water Act is to control point sources. Under the National Pollution Discharge Elimination System (NPDES), state environmental agencies authorized by the US EPA grant permits to point source dischargers such as municipal and industrial wastewater treatment plants (Faeth, 2000). The US regulatory approach for controlling nonpoint sources is completely different from that for controlling point sources. Both US EPA and the US Department of Agriculture (USDA) largely subsidise farmers to implement and improve nutrient management practices[8] rather than restricting them via permits (King & Kuch, 2003).

According to the US EPA's Water Quality Trading Policy published in 2003, a pre-specified Total Maximum Daily Load (TMDL) for the water body of concern serves as the baseline for trade. Trading partners covered by the same TMDL can trade relative to NDPES permits or NDPES permit holders may buy nutrient reduction credits[9] from nonpoint sources to offset additional discharges. US EPA (2007) identifies five ways that nutrient trade may take place.

1. Bilateral trade between two point sources.

2. Multilateral trade among many point sources.

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[8] Nutrient management practices which are also known as nutrient best management practices (BMPs) are farming methods that minimise nutrient loss from land uses. Some of those are using nutrient budgets and soil testing for optimal nutrients application, maintaining soil cover by leaving crop residues on the surface, establishing buffer areas between farms and environmentally sensitive areas, and slowing overland water flow through counter tillage, diversions, and sediment ponds.

[9] In the US nutrient trading systems, nutrient reduction credits are traded rather than nutrient permits. The two terms are different. A nutrient credit refers to a certain amount of nutrient load reduction. Credits are generated by nutrient management practices and abatement.

3. PS credit exchange: point sources which perform well below the permitted levels can save credits in an exchange which is overseen by a third party: government, private, or non-profit. Other point sources can buy credits from the credit exchange rather than buying directly from another point source.

4. Bilateral trade between point and nonpoint sources: point sources can buy credits from nonpoint sources which generate credits via best management practices that reduce pollutant loading to the receiving water body.

5. NPS credit exchange: A nonpoint source credit exchange is a centralized pool of credits maintained by a third-party who buys credits from nonpoint sources and sells to point sources. Nonpoint sources who implement best management practices can generate credits and sell to the exchange. Point sources may then purchase credits from the credit exchange.

Below we provide a brief overview of three nutrient trading programs in the US. More details on US nutrient trading systems are available in US EPA (2007).

The Long Island Sound Nitrogen Credit Exchange Program (Connecticut) allows trades between point sources of nitrogen. Seventy-nine municipal sewage treatment plants in Connecticut can participate in trading and the Connecticut Department of Environmental Protection (CDEP) oversees the trading system. The purpose is to control nitrogen loading to the Long Island Sound (LIS) estuary, a single receptor. CDEP use a water quality model of LIS and its major tributaries to determine the relationships between the discharge points and the actual delivery of nitrogen to the estuary. Trading ratios were determined to adjust for variability in delivery among sources. A set of zonal delivery factors (calculated from the LIS water quality model) accounts for the variability between actual discharge at the discharge point and delivery to LIS. Trading ratios are calculated directly from these delivery factors. In 2005, 50 municipalities had purchased credits and 28 had sold credits.

The Red Cedar River Watershed Nutrient Trading Pilot Program (Wisconsin) allows trades between point and nonpoint sources of phosphorus. Participants are the publicly owned treatment plants in the city of Cumberland and the farmers in the Red Cedar watershed. The treatment plants can buy phosphorus reduction credits from upstream farmers who implement nutrient management practices. The trading ratio applicable for all trades between point and nonpoint sources was 2:1, meaning that the treatment plants have to buy 2 kg nutrient reduction credits from farmers to match each unpermitted 1 kg of phosphorus discharge into the river. This fixed trading ratio was selected purely on negotiation between the environmental authority and the city's point sources. As at 2007, the treatment plants had purchased more than 60 best management practices (BMPs) from farmers.

The Lower Boise River Effluent Trading Demonstration Project (Idaho) allows trades between point and nonpoint sources of phosphorus. The TDML for Lower Boise River serves as the basis for trading. Point sources (waste water treatment plants and industrial dischargers) and nonpoint sources (farmers in the irrigation district) can participate in the trading system. Trading ratios apply for trades between point and nonpoint sources. The Idaho Soil Conversion Commission which oversees the trading system should approve the BMPs before being purchased. For each approved BMP, it assigns a specific trading ratio taking into account site location, phosphorus losses in the watershed, and losses due to irrigation withdrawals from the river. As at 2007, no trade had taken place.

US nutrient trading systems have two design-related pitfalls. The trading ratios used in the US, for point and nonpoint source trades in particular, are safety oriented and sometimes stricter than the theoretical non-degradation based ratios (Hoag & Hughes-Popp 1997). Such trading ratios restrict the opportunities for trade and increase the cost for buying point sources, but improve the water quality, or at least prevent any water quality deterioration as a consequence of trade. Some programs have a fixed trading ratio which applies to all trades, but some allow a series of pair-wise trading ratios which varies depending on the location of traders, the nutrient transport characteristics of the watershed, the pollutant traded, the level of uncertainty in delivery, and program goals (US EPA 2007). Even with a series of trading ratios, these bilateral trading ratio systems have high transaction costs and thin trading (David, 2003; Faeth, 2000; Fang, et al., 2005; Hoag & Hughes-Popp, 1997; King &

Kuch, 2003). There are only a few exceptions to this general trend; one is the nutrient trading systems in the Minnesota River Basin (Fang, et al. 2005).

Another problem in the US nutrient trading systems is ignoring the temporal impacts of nonpoint sources. All the trading systems discussed above are single receptor, single time period markets. In calculating the trading ratios, none of the US nutrient trading programs has taken into account the time lag between the implementation of nonpoint source BMPs and occurrence of nutrient loading reduction at a receiving surface water body. As a consequence, point source purchases of nonpoint source credits may increase pollutant loads in the short run.

Nutrient trading systems in the United States have many obstacles to trade. The first is that only point sources (mainly industrial) are regulated, while nonpoint sources (mainly agricultural) are not. Point sources, if they cannot meet the discharge limits specified by the permits, can pay upstream land users to implement best management practices which offset the excess nutrient load. Under the above circumstances, US nutrient trading systems are not true PS-NPS nutrient trading programs mainly because they do not require any purchases by NPS, and trades always occur in one direction. For at least 20 years, both economists and environmentalists have emphasised the need for regulating nonpoint sources as a means of encouraging them to actively participate in nutrient trading programs (Faeth, 2000, King and Kutch 2003).

4.10 Empirical Evidence: Lessons Learned

After almost 40 years of research and discussion on water pollution trading, only a few countries like the United States and Australia have active water pollution trading programs. The number of actual trades is growing slowly. As at 1997, five water pollution credit trading systems were in place in the United States but no trade had been made (Hoag & Hughes-Popp, 1997). As at 2003, there were about 37 nutrient trading programs in the US, but only seven trades had actually taken place (King and Kuck, 2003). As at 2007, many trades had been reported from the US water quality trading programs, but several trading programs reported no trades (US EPA, 2007).

The slow growing water pollution trading in the US has motivated a discussion on the factors that affect the success of such trading programs.

Hoag and Hughes-Popp compared the pollution permit trading theory with one application, the Tar-Pamlico nutrient-trading program in North Carolina. They identified six factors that had encouraged and discouraged trade: transaction costs, number of participants, abatement costs, enforcement costs, trading ratios, and loading limits.

According to Hoag & Hughes-Popp (1997) the Tar Pamlico trading system allowed trades at a fixed price (based on average cost). Trades at a fixed price reduced transaction costs but the traders were unable to derive the marginal cost benefits. By allowing trade between point and nonpoint sources, the system gained the advantage of having a greater number of participants and increased opportunities for trade. Hoag & Hughes-Popp argued that the safety netted (non-degradation based) trading ratios had increased the cost of trades. For point sources, allowable levels of emissions (as specified by the permits) exceeded the expected loadings, eliminating the need for trade. Based on the above observations, Hoag & Hughes-Popp recommended that the designers of such trading systems have to find a compromise between cost effectiveness, administrative simplicity and political acceptance. Including both point and nonpoint sources, improved knowledge of the relationships between sources and receptors, more cost effective trading ratios, and marginal cost pricing were also recommended for the success of water pollution trading systems.

David (2003) carried out a similar study on the failure of a discharge permit trading system for the Fox River in Wisconsin, United States. She also outlined some conditions required for a water pollution permit market to perform effectively: (1) potential cost savings from trade are substantial, (2) the expected emissions from the sources are greater than the current permit allocations, (3) treatment costs significantly differ among dischargers, (4) firms experience difficulties in meeting current discharge limits, (5) transaction costs are low enough to allow gains from trade, (6) property rights traded are well defined, (7) firms are certain of the opportunity to buy back in the future, (8) there are a sufficient number of potential buyers and sellers for a market to exist, (9) the process of validating trades is quick, and (10) firms know that they are penalised for violating permit limits.

King and Kuch (2003) studied the factors that kept nutrient trading in the United States rare and limited to a few trades. They found that institutional obstacles do exist but they are manageable, but insufficient demand and supply caused by federal and state subsidy programs that pay farmers to implement nutrient management practices are the main obstacles to trade. King and Kuch pointed out that the prevailing government policies do not stimulate demand and supply and policy changes are unlikely. Therefore, they argued that nutrient pollution trading systems should be implemented only in those watersheds where favourable demand and supply conditions exist.

Fang, Easter, and Brezonik (2005) discussed two exemptions from the general trend of few PS-NPS trades occurring in water quality trading systems in the United States. The two trading systems were found in the Minnesota River Basin. Two companies which owned point source discharge permits, Rahr Malting Company and Southern Minnesota Beet Sugar Cooperative, established the two trading systems to buy nutrient reduction credits from farmers. Pollutants traded were nitrogen and phosphorus. The researchers found that the offsetting nature of the two projects which required additional point source discharges to be fully offset by NPS best management practises and availability of information on potential nonpoint source trading partners have contributed to a relatively higher number of PS-NPS trades. These trading systems have not only reduced pollution, but contributed to further environmental protection and regional economic growth. Additional environmental benefits were achieved because both trading projects used a trading ratio equal or greater than 2:1 to account for uncertainties in equalizing nonpoint source loading to point source loading and to provide extra pollutant load reductions.

4.11 Conclusions

While permit trading programs have been successful in controlling air pollution, the results in the water quality area are not impressive (Faeth, 2000; Kochtcheeva, 2009).

Progress has been observed in trading point source water pollution permits, but the world has little experience with nonpoint source trading in general, and nitrate trading in particular. The United States is the only country which has active nutrient trading programs, but they are neither true nonpoint source trading systems nor point and nonpoint source trading systems. New Zealand has proposed tradable approaches for nonpoint source control, but the programs are at the design stage. The rest of the world is also still considering policy changes towards market based instruments and designing market mechanisms for controlling nonpoint sources.

Analytical literature highlights the importance of program design. Kochtcheeva (2009) emphasised that the program design, institutional settings, and supply and demand have significant effects on the performance of water pollution permit trading programs. Experience with air pollution trading suggests that two important factors have contributed to the success of air pollution trading: (1) creation of a tradable standardized commodity which is capable of achieving environmental goals and (2) ability to achieve the environmental goals at least cost by designing the trading program as efficiently and attractively as possible (Schary & Fisher-Vanden, 2004). In the next chapter, we will show in detail how difficult it is to define a common standardised commodity for trading water pollution. What could be done is to design the trading programs to be as efficient and attractive as possible so that the environmental goals can be achieved at least cost.

Chapter 5

5 The Problem of Trading Nitrates

5.1 Introduction

This chapter discusses the difficulties of trading nitrate discharge permits, and thus the important considerations for market design. We consider agricultural nonpoint sources from which nitrate leaches into the aquifers and consequently migrates to surface water bodies via groundwater flux, and municipal and industrial point sources from which nitrate is discharged directly into surface water bodies.

We first discuss the hydro-geological factors that should be considered in designing a market mechanism for allocating nitrate discharge permits. We discuss the additional issues that arise in trading nitrate discharge permits in the presence of multiple receptors and both point and nonpoint sources. We identify the basic requirements of a market-based mechanism for allocating nitrate discharge permits. We analyse the state-of-art solutions, previously proposed and currently available tradable permit systems, and show explicitly that these systems are unable to meet the environmental standards at least cost to society. Thus, we recognize the need for research into program design for trading nitrates. We analyse the designs of the market-based instruments for trading other resources such as electricity which have similar characteristics. Then we argue on the applicability of those market mechanisms for allocating water pollution permits, especially in the case of nitrates.

We use the term “farm” to refer an agricultural nonpoint source, an area of land within a catchment where some agricultural activities are carried out. The term “regulator” refers to a regional environmental authority that is responsible for maintaining water quality in the region. The regulator represents the government and acts on behalf of the public interest. We use the term “loading” to refer to nitrate loading or leaching into the aquifer from nonpoint sources and the term “emission” to refer to nitrate emission into a surface water body from point sources. Accordingly, a “loading permit” refers to a right to load a specified amount of nitrate into the aquifer during a specified time period, and an emission permit refers to a right to emit a specified amount of nitrate into a surface water body during a specified time period. The term “flux” refers to the discharge of nitrate into a surface water body through groundwater flux. Nitrate trading refers to trade in nitrate loading and emission permits.

5.2 Effects of Catchment Hydro-geology

We describe the hydro-geological factors that affect the trade in loading permits, using a small hypothetical catchment example discussed in Appendix B. Figure 5.1 provides a rough view of the catchment which drains to a stream. Rectangles indicate the nonpoint sources (farms) and circles indicate the point sources. The two crossed circles indicate drinking water supply wells (they are also water quality monitoring wells).

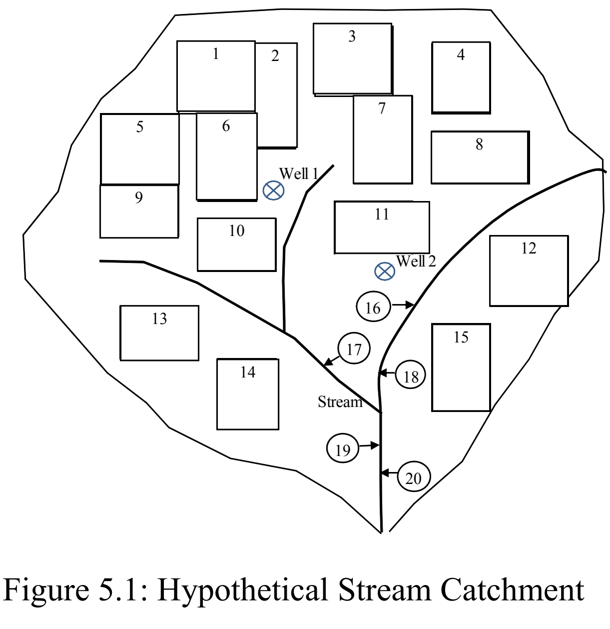

Figure 5.1: Hypothetical Stream Catchment

Assume that the regulator wishes to allocate loading permits among the farms for the upcoming year through a tradable permit program (a market mechanism), so that the nitrate flux into the stream does not exceed the predetermined water quality standards at any time. The graphs in Figure 5.2 below show the amount of nitrate expected to be delivered to the stream in each year since 2010, if 1 kg of nitrate were loaded into the aquifer during year 2010 from each of two farms in the catchment: farms 1 and 8.

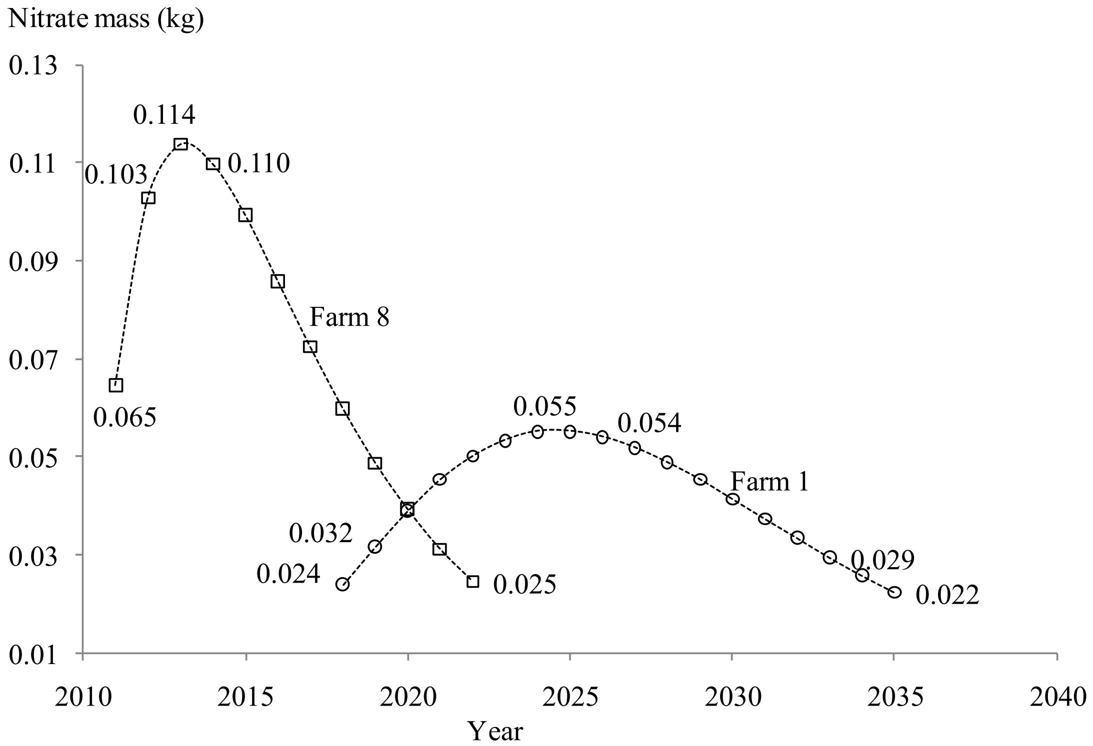

Figure 5.2: Amount of nitrate delivered to the stream from 1 kg nitrate loading in 2010 from farms 1 and 8.

The 1 kg of nitrate loaded from each farm is not delivered to the receiving water body at once. After a certain time delay, the pollutant mass is gradually delivered to the stream over a relatively long period. For example, nitrates leached from farm 1 do not appear in the stream until 2018 and thus farm 1 has a time lag of 8 years between loading and delivery to the receiving stream. From farm 1, 0.024 kg is delivered in 2018, 0.032 kg is delivered in 2019,…, and 0.022 kg is delivered in 2035. The delivery time span is 18 years (from 2018 to 2035). The delivery peaks in 2025 (0.055 kg). For farm 8, the time lag is just one year, the delivery time span is 12 years (from 2011 to 2022), and delivery peaks after 3 years (in 2013). Therefore, the time lag, time span of delivery, peak time, and the quantity delivered in each time period vary from source to source.

On the other hand, the total amount of nitrate loaded into the aquifer is not transported to the receiving water body in full, but only a portion is delivered due to hydro-chemical processes such as denitrification in the groundwater system. For example, only 0.743 kg of nitrate loaded from farm 1 (74% of the loading) is transported to the stream; the rest is lost in transport. From farm 8, 0.852 kg out of a 1 kg load (85%) is transported to the receiving water body. The amount of attenuation varies depending on the location of the farm relative to the receiving water body and the flow paths.

Let us assume a linear relationship between the quantity loaded from each farm and the quantity transported to the stream in each year. Then a 1000 kg loading permit held by farm 1 in 2010 causes no nitrate flux into the stream in year 2013 and a 55 kg nitrate flux in year 2025. Transferring this permit from farm 1 to farm 8 would cause a 114 kg nitrate flux in year 2013 but no flux in 2025. Therefore, a simple permit transfer between farms 1 and 8 would change the quantity of nitrate delivered to the stream in each year. The changes vary across time. The quantity delivered may be increased in some years and may be decreased in other years. Thus a transfer may degrade water quality in some years and improve water quality in other years.

Nitrate transport profiles (for the stream) of all fifteen farms in the catchment are shown in Figure 5.3. The graphs indicate that the time lags, attenuations, delivery time spans, and delivery peak times vary from farm to farm[10].

[10] The delivery profiles of the farms seem to have some patterns (for example, the longer the delay, the longer the delivery time span and the greater the attenuation). This is a specific feature of our example because it assumes that all the hydro-geological properties of the aquifer are uniform. This is not the general case because the aquifer properties usually change over space.

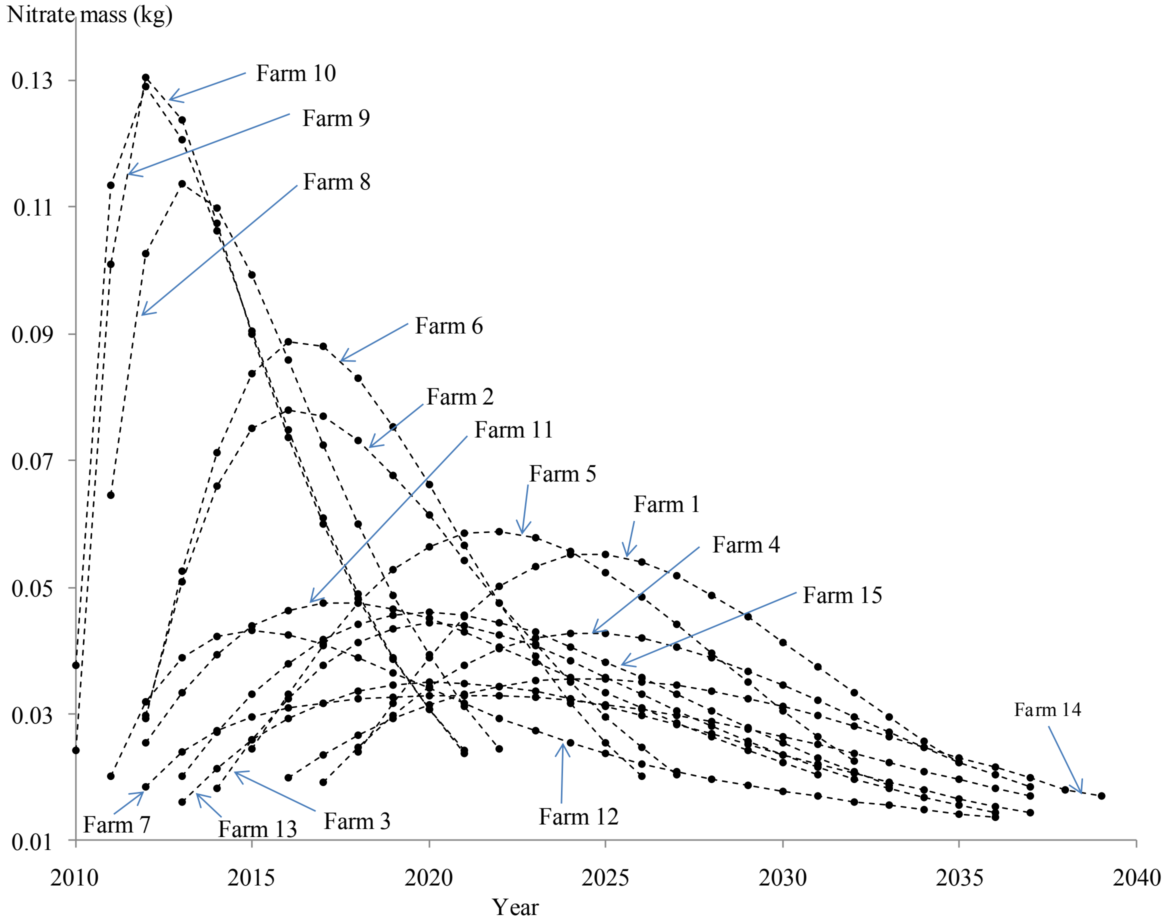

Figure 5.3: Amount of nitrate (kg) delivered to the stream from 1 kg nitrate loading in 2010 from each farm.

Based on the above observations we identify three important factors that should be taken into account in trading nitrate loading permits.

1. Time lags between leaching and appearance in a water body. Nitrate, once mixed in slow-moving groundwater, keeps on flowing with groundwater for decades until being discharged into a surface water body or the ocean. The time lags vary depending on the location of loading and varying hydro-geological properties of the flow paths.
2. Attenuation in transport. Nitrate flowing in water may be biologically or chemically transformed into other forms of nitrogen in the groundwater

system[11]. The amount of attenuation varies according to the properties of the subsurface strata and the length of the flow paths.

3. Protracted delivery profiles. The quantity of nitrate transported from a farm to some surface water body is not delivered in one step, but gradually over a relatively long period.

5.3 The Multiple Receptor Problem

The mass nitrate flux into a surface water body from its catchment alone may not be a reliable indicator of the catchment groundwater quality, but it is practically impossible to monitor and control nitrate levels at all locations in the aquifer. Therefore, catchment environmental authorities usually select a few groundwater monitoring wells where nitrate concentrations are monitored and controlled.

In the above example, we had only one receptor, the stream. We assumed that the regulator wanted to allocate loading permits though a tradable permits program to meet the water quality standards at a single receptor (the stream). Now assume that the regulator wants to allocate loading permits to meet the water quality standards in the stream and the drinking water wells. Then the situation becomes a multiple receptor problem, which is more complex.

Figure 5.4 shows the increases in concentration at wells 1 and 2 caused by 1 kg nitrate loading from each farm. On well 1, farms 1, 2, and 6 have considerable impacts, while other farms have zero or negligible impacts. On well 2, farms 7 and 11 have considerable impacts while others have zero or negligible impacts. In this example, each farm affects one well at most, but in general, a given farm may affect many groundwater wells. The graphs in the figure indicate that the farms have different temporal effects on the concentration of each well. On the other hand, the farms affect the wells and the stream in different time scales. For example, nitrate from farm 1 takes 8 years to reach the stream, but only two years to reach well 1.

[11] For example, by pyrite oxidation and biological denitrification (Conan et al. 2003).

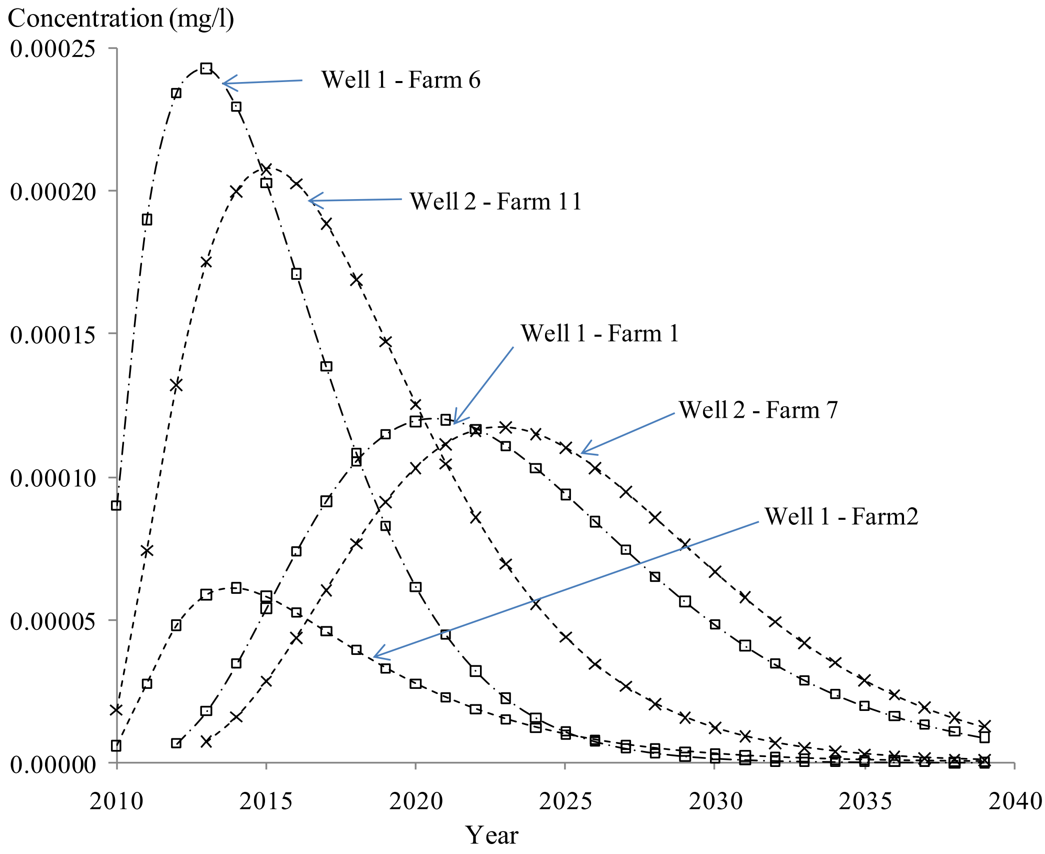

Figure 5.4: Increases in nitrate concentration at wells 1 and 2 caused by 1 kg nitrate loading in 2010 from each farm. Only farms 1, 2 and 6 have considerable effects on well 1. Only farms 7 and 11 have considerable effects on well 2.

Multiple receptor situations occur not only when the groundwater nitrate concentration is monitored and controlled at some monitoring wells, but also when large catchments have several connected stream segments and lakes, and the regulators want to control nitrate discharge into each of those surface water bodies. For example, the Lake Taupo catchment of New Zealand has several streams flowing into the lake. The Waitaki River catchment in New Zealand's South Island has several connected streams and lakes. In such cases, each connected stream segment or lake may be considered as a receptor.

Another possibility found in the literature is multiple (concentration monitoring) receptors on the same surface water body. Rather than controlling total nitrate discharge into the surface water bodies, the regulator may want to control nitrate concentrations at different points in a receiving surface water body. This is not a good idea, because the surface water concentration may vary due to the variations in surface water flow and quantity caused by rain, evaporation, and water diversions, rather than nitrate fluxes from the catchment. In this work, we do not consider multiple (concentration- monitoring) receptors on a single surface water body.

When multiple receptors are considered, the farms in a catchment may affect different receptors over different time scales. As a consequence, a permit transfer may improve the water quality at some receptors in some years, and degrade the water quality at some receptors in other years. Hence, when multiple receptors are involved, trades should satisfy water quality standards in every time period at every receptor.

5.4 Presence of Point Sources

Surface water bodies such as lakes and streams usually receive nitrates from both point sources and nonpoint sources. Ideally, all manageable sources including industrial and municipal point sources and agricultural nonpoint sources should be included in a catchment nitrate trading system. However, point and nonpoint sources differ significantly, and these differences can limit the effectiveness of integrated trading programs. These differences can also be illustrated using the hypothetical catchment example presented above.

1. Time lags. Since point sources discharge directly into the stream, with respect to the stream (receptor), the time lag for point sources is zero while the time lag for nonpoint sources may be decades. For example, a municipal sewage treatment plant may discharge directly into a stream with zero time lag, while nitrates loaded into the aquifer from an upstream farm may take decades to reach the stream via groundwater flux.
2. Attenuation and protraction: Point source emissions are received by the stream instantly in full quantity. As discussed above, nonpoint source loadings are not usually transported to a receptor in full or at once, but gradually over a relatively long period. Point source effects are not as protracted as nonpoint source effects.

3. Multiple receptors. While nonpoint sources affect groundwater receptors, point sources do not usually affect groundwater receptors (we have considered a catchment where groundwater flows towards a surface water body but not vice versa). But this may happen under extreme circumstances such as a flood. A flood may cause the surface water head to rise above the groundwater head allowing surface water to flow into the aquifer.

5.5 Requirements of a Workable Nitrate Trading System

The essential concerns for the optimal control of nitrate pollution for both market based and non-market based mechanisms were discussed in section 2.7. This section outlines the essentials of a market-based mechanism in particular. The success of any pollution permit trading system is determined by its ability to allocate pollution rights efficiently. As discussed above, an efficient market mechanism for trading nitrate must incorporate specific factors (for example, the catchment hydro-geology) in addition to the general factors that affect the success of any trading program (for example, low transaction costs).

5.5.1 The Commodities Traded

The major factor that has driven the success of air pollution trading systems is the creation of a tradable standardized commodity which is capable of achieving environmental goals (Schary & Fisher-Vanden, 2004). For any tradable permit program to be successful, to be accepted by the stakeholders, and to be implemented and maintained at a reasonable cost, the commodities traded should be clearly defined and standardised.

5.5.2 Information Requirements

Due to the delayed and dispersed nature of nitrate transport in natural systems, trading requires significant information about the fate of nitrates released from sources. First, trading systems need knowledge of the relationship between loadings and emissions at sources and their effects at the receptors (O'Shea, 2002).

Second, trading systems need reliable estimates of sustainable nitrate levels at the receptors to achieve the water quality standards in groundwater and surface water. These may be defined as maximum acceptable mass pollutant discharge into a receptor or maximum acceptable pollutant concentration at a receptor. Tradable concentration or mass should be set taking into account the contributions of unmanageable sources.

Third, to achieve the optimal allocation of pure public goods, even with a market-based instrument, some kind of government intervention is required, and the government who acts as a central planner needs critical information about the users, mainly, the user benefits of pollution (Baliga & Maskin, 2003). The market structure should be selected so that it incentivises the users to act on their true benefit functions (Egteren & Weber, 1999).

Fourth, availability of information about potential trading partners encourages trading (Fang, et al., 2005). This requirement is significant for free bilateral trading. In contrast, a centrally controlled market which operates as an exchange or a marketplace does not require much interaction and exchange of information between buyers and sellers (Woodward, Kaiser, and Wicks 2002).

5.5.3 Demand and supply

The major reason that few trades take place in the US nutrient trading systems is insufficient demand and supply (King & Kuch, 2003). Demand and supply are directly related to the number of buyers and sellers. Therefore, for a water quality trading system to function actively, there should be a sufficient number of potential buyers and sellers (David, 2003; Hoag & Hughes-Popp, 1997).

Demand and supply are strongly related to other factors such as prevailing restrictions on nitrate discharge (in a non-market situation), nitrate reduction targets at the receptors, the initial distribution of discharge rights, and the differences in nitrate abatement costs, discharge levels, and operations among the participants.

For the most part, demand and supply is beyond the control of market designers (King and Kuch 2003). However, some design features such as the scope of the trading system (focus on the catchment rather than a particular water body) and the method of initial allocation may be selected to improve demand and supply.

David (2003) found that for a trading system to function properly, firms should be certain of the opportunity to buy back in the future; this is also related to having sufficient demand and supply.

5.5.4 Trading rules

For a permit market to function properly, trading rules should be well established, understood, agreed upon, and adhered to. The trading procedure should be simple enough to understand. Over-restrictive trading rules cause thin permit markets and market failures (Faeth, 2000; Hoag & Hughes-Popp, 1997). On the other hand, loosely defined trading rules may end in unfair trading and non-attainment of environmental goals. Some trading rules allow “free-rider” problems which arise when some polluters benefit from the transactions of others and lead to thin markets (McGartland, 1988).

5.5.5 Transaction costs

Theory and experience in pollution permit trading suggest that the transaction costs can cause market failures (Hoag & Hughes-Popp 1997; McGartland 1988; David 2003). In a nitrate permit market, the cost of finding trading partners, negotiating prices and contracts, obtaining approvals (validating trades), preparing agreements, and related legal deals contribute to the overall transaction cost. The market structure should be selected to minimize the transaction costs.

5.5.6 Monitoring and Enforcement

A healthy market requires sufficient monitoring and enforcement. Discharge rights should be well defined, stating what the permit holders are allowed and not allowed by the permits. Firms should know that they will be penalised for violating permit limits (David 2003).

Monitoring point source nutrient discharge is easy with the available technology, but monitoring nonpoint source nitrate loading is difficult. Since nitrate loading from agricultural nonpoint sources depends on the type of land use and land management practice, land uses may be monitored in addition to the quantitative nitrate losses. To accomplish proper monitoring and enforcement, the methods, procedures, and devices used should be well defined under trading rules.

5.6 State of the Art: Alternative Solutions

Based on our literature survey and the requirements of nitrate permit trading, we identified two quite different market approaches as candidate solutions for the problem of trading nitrate permits: free trading of receptor permits and centrally controlled multilateral trading of loading (source) permits.

5.6.1 Free Trading of Receptor Permits

A receptor permit is a right to increase pollution (nitrate level) at a specified receptor in a specified time period. Under a receptor permit system, farms have to maintain a portfolio of permits to match the effects on each receptor in each period. For the above example, receptor permits may be defined separately for the stream and the drinking water wells, as rights to discharge nitrate into the stream in each year, and rights to increase the nitrate concentration in the well in each year. A farm's maximum allowed nitrate loading is determined by the bundle of receptor permits held[12].

The dispersed nature of nitrate transport requires the farms to maintain a wide variety of permits in each year. In the example given above, loading from farm 1 during a single year affects the stream over 18 years and groundwater well 1 over 15 years (if the effects of magnitude less than 0.00005 mg/l were ignored). The farm will have to surrender different quantities of 18 permits for the stream and 15 permits for the well to cover the operations in each year. Farmers may be utterly confused by such a

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[12] The receptor permit system discussed here is a generalised form of the ambient permit system discussed in the literature. The conventional ambient permits are not time specific, but the receptor permits discussed here are rights to pollute a receptor in a specified time period.

permit system. We have already discussed the administrative difficulties and transaction costs associated with such ambient permit systems (section 4.4.1).

To avoid sources having to maintain a complex portfolio of permits every year, and to eliminate the associated confusion and transaction costs, recent research has developed some simplification methods. First and foremost, for a receptor based permit program to work, only one or few receptors should be taken into account. For a catchment scale permit program, it is reasonable to consider the main water body towards which the catchment drains (in our example, the stream), as the single receptor. The permits can be defined as rights to discharge nitrates into the receptor. However, a single receptor alone does not free the farms from the burden of having to assemble a portfolio of permits because their nitrate loading in a single time period may affect the receptor in many time periods. Hence, another simplification criterion has to be adopted to avoid the farms having to assemble a portfolio of temporal receptor permits.

Kerr and Lock (2008) proposed to assign each farm to a single year or a block of few years (of lag time), and to require each farm to buy a single permit for the particular year or block (section 4.7). This approach approximates the bell-shaped temporal transport profile to a straight line representing the average impact as shown in Figure 5.5. Trading based on such approximations ignores some of the temporal impacts of nonpoint sources and may end in unexpected or increased levels of nitrates at the main receptor.

The biggest challenge in implementing the method proposed by Kerr and Lock (2008) is distinguishing non-overlapping blocks and assigning each farm to a single block. As shown in Figure 5.4, farm 1 peaks during the 14th to 18th years of loading and farm 2 peaks during the 3rd to 7th years of loading. There is no way to define sequential and continuous 5 year blocks so that each farm can be assigned to a single block based on peak 5 year effects. Further reducing the block length would lead to further unrealistic approximations.

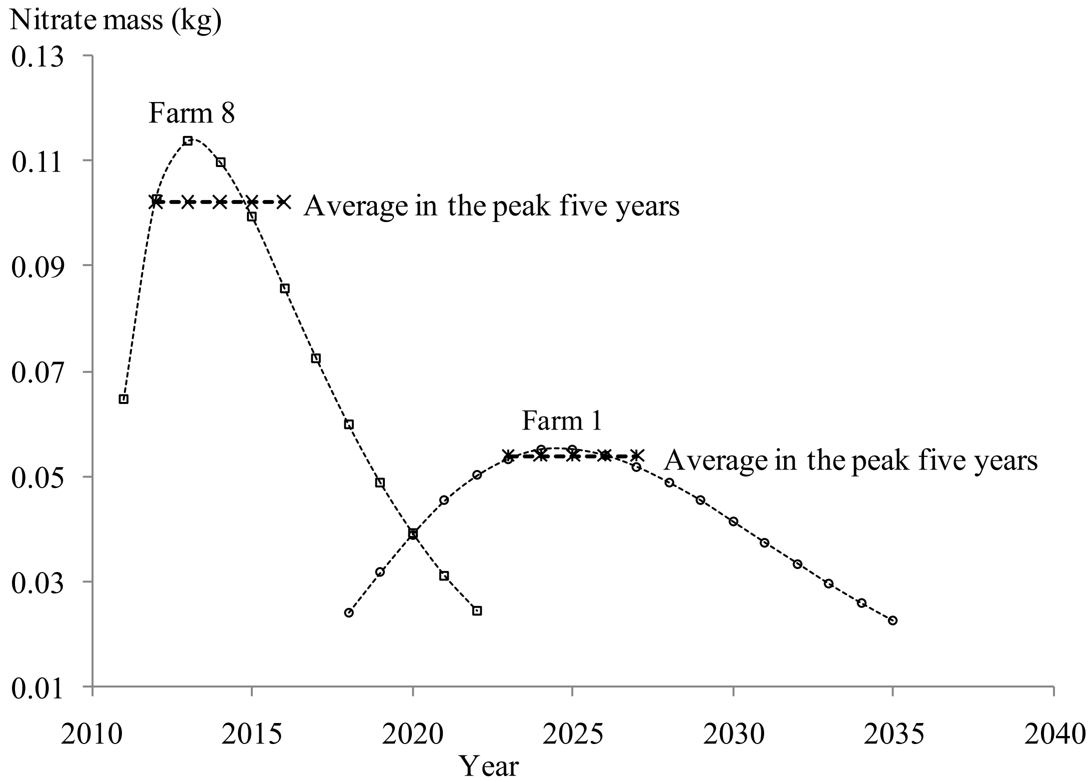

Figure 5.5: Approximation of the temporally varying effects of nonpoint sources to a series of uniform effects. The average effects of farms 1 and 8 over the peak five years.

Such systems limit inter-block trading opportunities to trades across time. As shown in Figure 5.5, in 2010, farm 1 needs 2023 to 2027 permits and farm 8 needs 2012 to 2016 permits. Any farm cannot purchase current permits from the other for immediate use. However, farm 8 may buy permits from farm 1 and use them in future. Such trades which induce compliance activities at different stages of time are usually known as trades across time.

Another simplification adopted by Morgan et al. (2000) assumes continuously valid permits (permits valid for *T* years) defined based on the last year of the planning horizon. A permit gives the owner an explicit right to increase the concentration at the selected receptor by a specified amount in the last year of the planning horizon. As we have discussed in Chapter 4 (section 4.7), this work is theoretically incorrect and such permits cannot achieve the water quality standards.

Kerr and Lock (2008) and Morgan et al (2000) have considered only a single receptor situation with nonpoint sources, but both cases include a large number of constraints (a constraint for every year during a long planning horizon). The common pitfall in those proposed trading programs is that they ignore some important constraints to simplify the problem. Such systems are unable to ensure water quality over time and can lead to unexpected results.

5.6.2 Centrally Controlled Multilateral Trading of Loading Permits

Loading permits are similar to emission permits discussed in the literature. Characteristics of the nitrate trading problem discussed above and the literature discussed about emission trading systems, for example, Ermoliev (2000) and Morgan, Coggins, and Eidman (2000), provide evidence that a centrally controlled multilateral trading framework is required to facilitate trade in loading permits (Chapter 4). We have already discussed the problems associated with other emission trading systems such as pollution offset systems and trading ratio systems (Chapter 4). In brief, those bilateral trading systems have free rider problems, high transaction costs, thin markets, and they cannot lead to efficient allocation of loading permits.

Loading permits can be traded in an exchange-type centralized market in which multilateral transactions are coordinated by an authorized entity. For trading nitrate permits, a centralized ex-ante market (possibly a year-ahead market) is suitable to achieve environmental feasibility, but they require the market coordinator to find the equilibrium prices ex-ante. The problem is how to find a set of equilibrium prices which rations the permits relative to each farm's profit/cost function while meeting the environmental standards over multiple receptors and time periods. Ermoliev et al. (2000) proposed that a market coordinator who acts as a Walrasian auctioneer could lead a centrally controlled permit market towards a set of equilibrium ambient (receptor) prices and emission (loading) prices (section 4.4.5). However, the auction may take a long time to converge to an equilibrium.

To find the equilibrium prices, a Walrasian auction is not required if the dischargers provide the coordinator information on quantities they would trade at each possible price step, beforehand. The optimal allocation may be modelled as a mathematical program, possibly as an LP, from which the equilibrium prices may be obtained straight off. This is the lesson that the environmental policy makers could learn from the modern electricity markets, which use LPs to clear the markets and set the prices instantaneously (Alvey, Goodwin, Xingwang, Streiffert, & Sun, 1998; Hogan, Read, & Ring, 1996). The similarity is that both are common pool, multilateral trading problems with complex interactions and a large number of interdependent and interrelated constraints. Given that the gains from trade and constraints on trade can be modelled linearly, the two problems have a close analogy. An added benefit is that not only the environmental constraints, but all relevant political, regional, and private constraints could be included in the pricing models, if justified by the stakeholders.

In the next section, we discuss the structure of modern electricity markets to understand how electricity is traded. Electricity, unlike other commodities, cannot be physically exchanged between any two parties as and when they wish. Trading should take into account a wide range of physical and economic constraints. This is the core issue with trading nitrate permits also. The design of electricity markets provides guidance for centrally controlled multilateral trading of nitrate permits.

5.7 Electricity Markets

In many parts of North America, Europe and Asia-Pacific, the electricity sector is de-regulated. The governments have established market mechanisms to meet demand as efficiently as possible, in a way which is acceptable to both producers and consumers. Most modern electricity markets are centrally controlled online trading programs which facilitate multilateral trading through a common pool. They use optimisation algorithms to determine the generation dispatch schedules and prices (to clear the market), maximising the gains from trade relative to the submitted bids and offers. Electronic markets supported by optimisation methods are sometimes called “smart markets” (McCabe, Rassenti, & Smith, 1991). The main features of smart electricity markets are listed below.

1. A common pool of resources or commodities.
2. Decentralized buyers and sellers.

3. A centralized decision maker or a regulator.
4. A framework for multilateral trading.
5. Bids and offers revealing willingness-to-pay and willingness-to-accept.
6. A mathematical programming model to clear the market periodically.
7. Constraints on capacity, budget, and/or transport.
8. Online trading.

In a smart market, buyers are buying from and sellers are selling to an exchange market or an auction rather than trading bilaterally with a trading partner. Ownership rights are transferred, and resources or commodities are added in and removed from a common pool rather than being physically transferred between individuals. For example, in electricity markets, buyers and sellers submit bids and offers to an online auction and pay or receive money according to the prices and quantities cleared. Suppliers supply electricity to the transmission network (pool), and consumers consume electricity from the network. This mechanism significantly reduces the costs of searching for trading partners and trading information, arranging contracts and agreements, and related legal procedures. Therefore, smart markets have low transaction costs.

When complicated interactions and externalities arise in trading resources through a common pool (for example, a farm's nitrate loading into groundwater has complicated impacts on the nitrate concentration in drinking water wells and nitrate fluxes into surface water), the process of market design is also complicated. Electricity markets and other smart markets (for example, the Victoria gas market in Australia) handle such interdependencies efficiently by including all those interactions in the mathematical programming models used to clear the market. Hence, the real strength of this market mechanism is the use of mathematical programming.

Electricity market clearing models used in New Zealand, Australia, Singapore and parts of North America are based on Linear Programming (Read and Chattopandhayay, 1999).

5.7.1 LP Models for Clearing Electricity Markets

Read and Chattopandhayay (1999) provide a nice overview of the structure of LP based electricity market clearing models. The basic purpose of electricity market models is to "maximise the benefits from trading in a spot market subject to the operating constraints". The electricity sellers (generators) and buyers (loads) in each region (node) submit offers and bids. The linear program finds the optimal set of generation offers and load bids which maximise the benefits from trading (as shown by the shaded area in Figure 5.6), taking into account a complex set of constraints on generator capacities, consumption, transmission line capacities, and system security and reliability requirements. The nodal demand and supply balance constraints ensure that the primary purpose of meeting the demand is achieved.

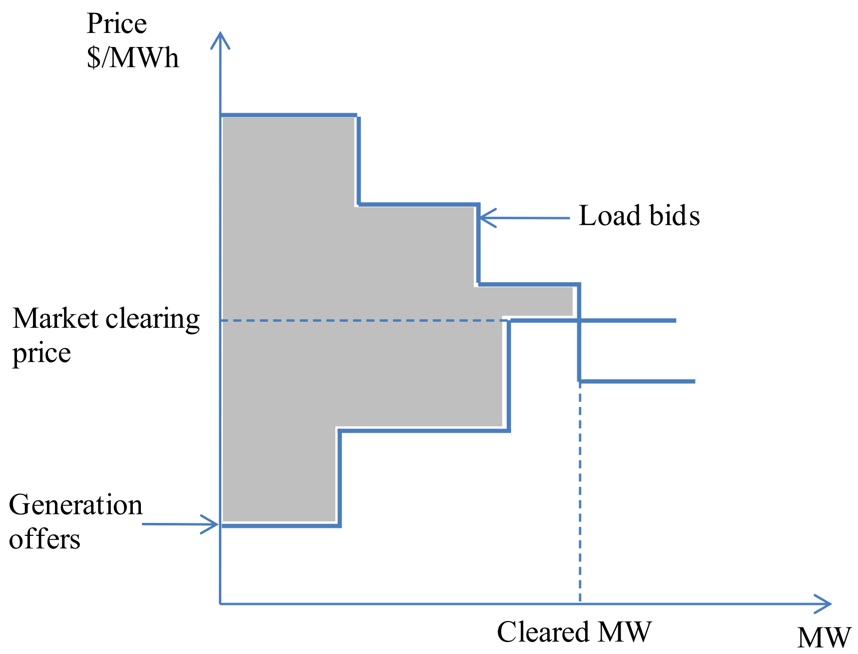

Figure 5.6: Overview of Electricity Market Clearing Models, Source: Read and Chattopandhayay (1999).

The main outputs of the LP models are the generation dispatch schedule (how much power is bought from each generator, how much power is sold to each retailer or user) and a set of nodal energy prices.

The markets are usually cleared at fixed time intervals, for example, every thirty minutes. Market clearing for any time interval means solving the LP with the set of bids and offers submitted for the particular period and finding the optimal dispatch schedule and prices for the period. Since electricity markets are frequently cleared, payments and charges are not cleared immediately but at longer time intervals, for example, the end of every month.

5.7.2 The New Zealand Electricity Market (NZEM)

New Zealand was a pioneer in electricity market research, design, and implementation (Alvey, et al., 1998; Hogan, et al., 1996). New Zealand's electricity market, known as the NZEM, is an online trading system run by agreed rules. Electricity generators offer electricity to the wholesale market for dispatch via the countrywide transmission system known as the "national grid". Electricity retailers bid online to buy electricity to supply their customers. The online trading system processes the bids and offers and updates the prices every five minutes. Virtually, electricity is supplied to the end users via retailers. Consumers are free to select and change their retailers any time.

The government oversees the trading system through an authorized institution called the Electricity Commission. The commission has out-sourced the services required for the market. Most of the operational activities are contracted to a company called NZX, while the transmission network is operated and maintained by a state owned company called Transpower. Generation companies, retailers and large electricity users participate in the market.

5.7.3 Smart Markets for Environmental Pollution Rights

MaCabe et al. (1991), in their paper on smart markets, mentioned that this mechanism is applicable for the allocation of pollution rights where spatial contiguity is important. Murphy, Dinar, Howitt, Rassenti, and Smith (2000) designed a smart computer-assisted spot market for allocating water. Using a case study of the California water transfer system in the United States, they showed the efficiency gains of a smart market relative to conventional bilateral trading. Murphy et al. also mentioned that smart markets are applicable for allocating tradable pollution rights.

Raffensperger and Milke (2005) went a step further to design a smart market for groundwater, taking into account the hydro-geological effects of groundwater extraction in a more precise manner. In many ways, this market design is similar to the NZEM, mainly the market is cleared using an LP which maximises gains from trade relative to submitted bids and offers subject to constraints which describe the physical interactions of the system. However, the underlying interactions in water trading and electricity trading are different and the constraint structure is different. Raffensperger and Milke used a groundwater hydrology model (MODFLOW) to obtain a set of response coefficients which measure the drawdown in groundwater head at each head control location due to a unit groundwater withdrawal from each well. Using these coefficients, the groundwater head and total drawdown response at each control location are stated as a linear functions of extractions. The LP determines the optimal abstraction rates for all the wells, which maximise the gains from trade (consumer and producer surplus), subject to constraints on minimum and maximum acceptable groundwater head and drawdown at each control point. The smart groundwater market of Raffensperger and Milke would perform best as long as the responses to groundwater extraction are linear.

Even though the applicability of the smart market approach to trading environmental pollution permits has been recognized, a detailed market design has never been proposed, particularly for the nonpoint source pollution problem. The difficulties of modelling the physical interactions in the system, lack of information, and the cost involved may have hindered the effort. In the next section we show that none of the above problems are significant in designing a nitrate trading program.

5.8 Discussion

As promised in the previous chapter, we showed that defining a common standardised commodity to enable a free market in nitrate loading permits is impossible. Despite the economic theory on the ability of free markets to achieve the optimal allocation of resources without government intermediation, resources such as electricity, groundwater, and pollution rights cannot always be freely traded one-to-one based on private negotiations. However, the efficiency gains from market-based mechanisms compared to government regulation are well-recognised. Hence, despite the difficulties, market-based instruments have been devised to trade them efficiently. These are necessarily centrally controlled trading programs rather than "free" markets.

Modern electricity markets use LP models to find the generation and dispatch schedules and nodal prices that maximise the benefits from trading while satisfying complex sets of constraints which describe the physics and economics of the overall system. Water pollution permit trading is also a common pool resource allocation problem with complex interactions and externalities, similar to the problems of buying and selling electricity. Therefore, we conclude that the design concepts of the electricity markets have a great potential for application in water pollution permit trading. The literature discussed on non-market based mechanisms for the optimal control of water pollution (Chapter 3) provided evidence that it is possible to acquire the information required and to model the physical interactions in the system.

However, there are some criticisms of electricity markets and other smart markets. First, the efficiency gains of those centrally controlled bid/offer-clearing markets are questionable. According to fundamental economic theory, a market is efficient if it produces the maximum social benefit, taking into account the benefits derived by consuming and the costs incurred in producing. For a centrally controlled bid/offer based market to be efficient, the seller offers should indicate the true marginal costs and buyer bids should indicate the true marginal utility, so that the aggregate bid and offer functions (Figure 5.6) indicate the overall industry demand and supply functions. Otherwise, the outcomes may be inefficient. In practice, active market participation of a large number of rational buyers and sellers who cannot affect the prices creates relatively efficient markets. Hence, if the number of pollution sources (mainly agricultural entities) in a watershed is large, a permit market is likely to perform efficiently.

Second, the initial cost of setting up a smart market and the cost of operation may be significant. It is an interdisciplinary effort which needs engineers, economists, modellers and other relevant professionals. They need a lot of information. For electricity markets, the technology infrastructure should be in place and reliable, continuous monitoring and enforcement are required, and errors and pitfalls in the market design may end in catastrophe. However, electricity trading is a more dynamic business compared to trading nitrate permits. The demand for nitrate discharges does not vary as frequently as the demand for electricity. Hence, we can take only the relevant features of electricity markets, mainly the use of mathematical programs to determine the optimal prices and traded quantities, but not the dynamic operational aspects such as online trading and electronic monitoring and surveillance systems, though these features would be great if they could be done.

The main purpose of this thesis is to design a market mechanism for allocating point and nonpoint source nitrate discharge permits using mathematical programming techniques for pricing and allocation. We contribute to program design aspects with a focus on using the mathematical programs for pricing and allocation.

Chapter 6

6 TRADING NITRATE LOADING PERMITS[13]

6.1 Introduction

This chapter presents a market mechanism for allocating nitrate loading permits among nonpoint sources. The chapter focuses on the design of a trading program to use an LP to price and allocate loading permits over time and space. The trading schema is initially designed assuming that the environment, and thus the ability of the water bodies to tolerate pollutants (in this case, nitrate), are owned by the government (regulator) on behalf of the public. The trading system allows the government to lease-out the ability of the environment to accept pollution for short term use of the agricultural nonpoint sources, through nitrate loading permits. The sources can lease-in loading permits (buy) for up to a fixed number of years, and sub-lease previously leased permits (sell).

We first clarify the type of commodities (resources) traded in the market followed by a discussion on defining the scope of the trading system. Then we explain how to calculate the tradable quantities of those resources. We present an adaptation of the response matrix technique to relate the loading permits allocated to diffuse sources and the pollution that occurs at the receptors. We discuss the factors that should be taken into account in selecting the time frames for trading and make recommendations

[13] This chapter is based on Prabodanie, Raffensperger, Read, and Milke (2010).

for best compromise solutions. Finally, we present an overview of the market design, trading procedures, regulations, and operational aspects.

6.2 Commodities Traded

Trade is the exchange of commodities, and markets are places where commodities are traded. In an electricity market, it is clear that the commodity being traded is electricity. Both supply and demand are measured in Mwh of electricity. However, in a market for nitrate loading permits (or water pollution permits in general), the commodity or the resource being traded is not obvious.

Consumers wish to buy rights to load nitrates into the aquifer or some water body. A "loading permit" is a right to load a specified amount of nitrate into the aquifer from a specified location, in a specified time period. As discussed in section 6.6, we consider loading permits defined for each year separately.

The demand is for nitrate loading measured in kg, but the supply of loading rights is not directly limited in terms of total available kilograms, but indirectly restricted by the water quality standards specified in different units. Generally, water quality standards specify the maximum sustainable amount of nitrate that a water body can accept and dilute in a given time period without compromising its ecological health, survival, and quality. Therefore, the scarce resource which limits the farm nitrate loading is the ability of the concerned water bodies to accept nitrates. The commodity actually traded in a market in nitrate loading permits is the right to consume these resources.

We define a "receptor capacity right" as a right to increase the nitrate level at a specified receptor in a specified time period. A loading permit is therefore equivalent to a bundle of receptor capacity rights (commodities). The trading system should be designed to facilitate the farms to trade different bundles of commodities in the same exchange market.

For agricultural nonpoint sources, the tradable permits may be defined as "input permits" which allow the farms to adopt farming practices that cause nitrate loading. For example, permits may be defined in terms of maximum allowed nitrogen fertilizer application rate, stocking density, or effluent irrigation rate. However, the literature provides evidence that loading permits are more efficient than input permits (Horan, Shortle, & Abler, 2002). Under an input-based permit system, the farms may have to assemble different types of input permits to cover their operations. This is an unnecessary burden, because the commercial farmers have sophisticated tools (such as OVERSEER to relate the inputs to loading and to calculate the potential nitrate loading from intended farming options (section 2.4.3).

6.3 Scope of the Trading System

The trading system is designed at the catchment scale, but the traded commodities are defined relative to the set of receptors considered. Hence, the scope of the trading system is actually determined by the set of receptors selected. A catchment is generally defined as a land area from which water drains towards a common water body. Therefore, any catchment-scale water pollution trading system should consider the common sink, towards which the catchment drains, as the *main receptor*. Mass nitrate flux into the main receptor via groundwater is a good indicator of diffuse nitrate discharges in the catchment. Large catchments can have sub-catchments draining to small connected streams or lakes which may also be considered as receptors to avoid excessive local pollution. In addition, groundwater monitoring wells may be considered as receptors where the nitrate concentration in the well is controlled rather than the mass nitrate discharge.

Groundwater quality management models are sometimes developed considering a set of groundwater receptors only (C. L. Morgan, et al., 2000; Peña-Haro, et al., 2009). However, since a groundwater monitoring well is affected only by the sources whose nitrate travels through the well, the monitoring network should be designed to capture the effects of all sources. A large number of receptors may cause difficulties to the market authorities because they will have to set quality standards for each receptor and monitor each receptor. On the other hand, groundwater receptors cannot capture the effects of point sources. Therefore, we recommend a main surface water receptor with or without groundwater receptors.

Once the set of groundwater and surface water receptors are chosen, manageable nonpoint sources in the catchment, and manageable point sources that discharge effluents directly into the surface water receptors can be included in the trading program.

6.4 Tradable Capacities

We define “receptor capacity” as the amount of nitrate that a receptor can tolerate in a given time period without compromising its health and quality (nitrate intake capacity of a water body). The ability of the receptors to accept nitrate can vary depending on the weather, water use, and other factors. However, during a relatively long period like a year (which covers a whole hydrological cycle or several cycles), the receptor capacity can be estimated as a fixed value. Receptor capacities are estimated based on the general water quality standards discussed in section 2.6.3.

General water quality standards specify maximum acceptable pollutant concentrations in water used for specific purposes, for example, the maximum acceptable nitrate concentration in drinking water is 50 mg/l. Based on these general standards, regional environmental authorities develop specific water quality standards for specific water bodies or receptors. For example, the estimated maximum acceptable nitrogen load for Lake Rotorua is 435 tons per year (Rutherford, 2008). This is the amount of nitrate that the lake can tolerate in each year and hence the annual nitrate intake capacity of the lake. Receptor capacities may be specified in several ways, depending on the type of receptor.

1. The maximum acceptable mass nitrate discharge to a receptor during a time period, measured in mass units, e.g., kg, and specified for receptors such as lakes.
2. The maximum acceptable nitrate concentration at a receptor, at a time, measured in concentration units, e.g., mg/l, and specified for receptors such as groundwater wells.
3. The maximum acceptable mass pollutant flux at a receptor, at a time, measured in flux units, e.g., kg/day, and specified for receptors such as streams.

In this work, we consider the first two types of receptors only, surface water receptors for which the capacity is given as a maximum acceptable mass load, and groundwater receptors for which the capacity is given as a maximum acceptable concentration. The total capacity of the receptors may not be tradable due to the presence of unmanageable sources.

6.4.1 Tradable Sources

All the manageable nonpoint sources in a catchment (section 2.6.2) are usually considered as tradable sources. The main tradable sources are the agricultural land uses and we continue to use the term "farm" to refer to tradable nonpoint sources in the catchment. However, any land use which causes nitrate leaching should be considered as a tradable source. To be tradable, a source should be manageable or controllable by human intervention and be identifiable with an individual or an organization that is responsible for the source. Waste land fill areas and leaky wastewater or sewage tanks can be considered as tradable nonpoint sources, but some manageable sources may not be considered as tradable for social and political reasons.

6.4.2 Non-tradable Sources

Non-tradable sources are the sources of nitrate which are unmanageable and cannot be related to an individual entity responsible for that source.

The major non-tradable source is the groundwater nitrate storage: nitrates already in the aquifer leached from earlier land uses and currently travelling with groundwater. As mentioned in Chapter 2 (section 2.6.2), nitrate in upstream groundwater is a source of nitrate in downstream groundwater, and groundwater seepage is a source of nitrate in surface water. Nitrate flowing with groundwater is usually unmanageable. Natural sources, such as rain water, head waters, aquatic species, and unmanaged storm water are also non-tradable.

The "tradable receptor capacities" should be calculated after all non-tradable sources are accounted for. For example, according to Rutherford (2008), the total annual nitrate intake capacity of Lake Rotorua, is 1926 tonnes (equal to 435 tonnes of nitrogen, assuming all nitrogen that enters the lake is in the form of nitrate). The estimated annual nitrate contribution from sewage is 133 tonnes (30 tonnes/ of nitrogen) and is considered non-tradable. If there are no other non-tradable sources, then the tradable nitrate intake capacity of the lake is 1926 – 133 = 1793 tonnes/year (405 tonnes/year of nitrogen).

Apart from non-tradable sources, allocations may be made for other concerns such as uncertainties in capacity estimates and future demand. In Chapter 9, we discuss more about calculating tradable receptor capacities.

6.5 Linkage between the Sources and Receptors

We use the response matrix technique (Chapter 3) to relate nitrate loading from spatially distributed farms to the water quality deterioration at the receptors. Following previous work on optimal management of nitrate loading such as that of Morgan and Everett (2005), we assume a linear relationship between the loading and the increase in nitrate level at each receptor in each time step. By assuming linearity, we can calculate the increase in nitrate mass or concentration caused by each source at any receptor, in any time step, as the product of the source loading and the relevant response coefficient[14].

An important requirement for the application of the response matrix technique is that the source water flow rates are fixed, and therefore, the diffuse sources have fixed impacts on the groundwater flow velocities (Gorelick & Remson, 1982). The assumption implies that the aquifer recharge from each farm is fixed, and independent of the operating scale (stocking rate, fertilizer application rate, etc.) which can be affected by the permit allocations. In simulating nitrate transport in groundwater, recharge is usually estimated based on rainfall and evaporation data, ignoring the effects of land use and irrigation (Hadfield, 2008; Rekker, 1998).

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[14] With regard to response coefficients, the terminology found in the literature is inconsistent. Different terms such as transport, diffusion, response, or influential coefficients have also been used. In this thesis, we use the terms response coefficients and response matrix

For the assumption of linearity to hold, both the receptors and what is controlled at the receptors should be selected carefully. It is generally accepted that mass nitrate discharge to a surface water body from its catchment, and nitrate concentration in groundwater discharge from a catchment, have strong linear relationships with nitrate loading in the catchment (Rao, et al., 2009). Therefore, as mentioned in section 6.4, the most suitable receptors are streams, rivers, or lakes where mass nitrate input from the catchment is controlled, and groundwater monitoring wells where nitrate concentration is controlled.

6.5.1 Response Matrix

As receptor capacities, the response coefficients may be defined in several equivalent ways depending on the sources and the receptors concerned. As in Morgan & Everett (2005), this work uses two types of response coefficients.

1. Discharge (mass) response coefficients: the mass nitrate discharge into a receptor during a given time period, from one unit of nitrate loading from a pollution source during a certain time period, measured in mass units, e.g., kg, and used with receptors such as lakes.
2. Concentration response coefficients: the concentration that occurs at a receptor, at a given time, from one unit of loading at a pollution source during a certain time period, measured in concentration units, e.g., mg/l, and used with receptors such as groundwater wells.

The previous applications of the response matrix method to describe nitrate transport in groundwater, for example, Peña-Haro et al. (2009) had a response coefficient to measure the increase in nitrate level that occurs at each receptor, in each monitoring time step, from one unit nitrate loading from each source, during each management period. Having a response coefficient for each management period is useful when the length of the management period can vary and can start from different points in time, but the set of management periods should be pre-defined, and a large number of simulations may be required to construct the response matrix.

In our problem, the management period length is fixed to one year (because loading permits are defined for a single year), but can start from different points in time. For example, a farm may want to buy a permit for the next year (2011), for a later year (2015), or for each of the next five years from 2011 to 2015 (five permits starting from different points in time). The set of management periods cannot be pre-defined because it depends of what the farms will need to buy (subject to market regulations). Therefore, we have to adapt the response matrix technique to suit our purpose.

Assuming that the groundwater flow system is in a steady state where groundwater flow terms do not vary over time[15], we develop a *reduced* (delay-based) response matrix which specifies the response coefficients relative to source, receptor, and *time delay*, allowing dynamic calculation of response coefficients for different management periods. Since the response coefficients used in this work are not indexed over the management periods, our method is more efficient than the response matrix used in previous work.

6.5.2 Reduced (Delay-Based) Response Coefficients

If the groundwater flow system is in a steady state, and hence the groundwater flow terms are constant over the whole period, nitrate loading from one farm in any year would have the same profile of effects on a given receptor. The series of effects would start from a different point in time depending on the time of loading. Based on the hypothetical catchment example discussed in Appendix D, Figure 6.1 shows the series of effects that nitrate loading in farm 1 during years 2010, 2011, and 2014 would have on the stream (observed from a steady state simulation). Each series is the same quantitatively, starting from 8 years of loading. Hence, we can construct the aggregate effect profile of loading over the five consecutive years starting from 2010 by aggregating the five offset copies of the same one year profile.

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[15] Note that the response matrix technique is generally applicable under both steady-state and transient conditions (Gorelick & Remson, 1982).

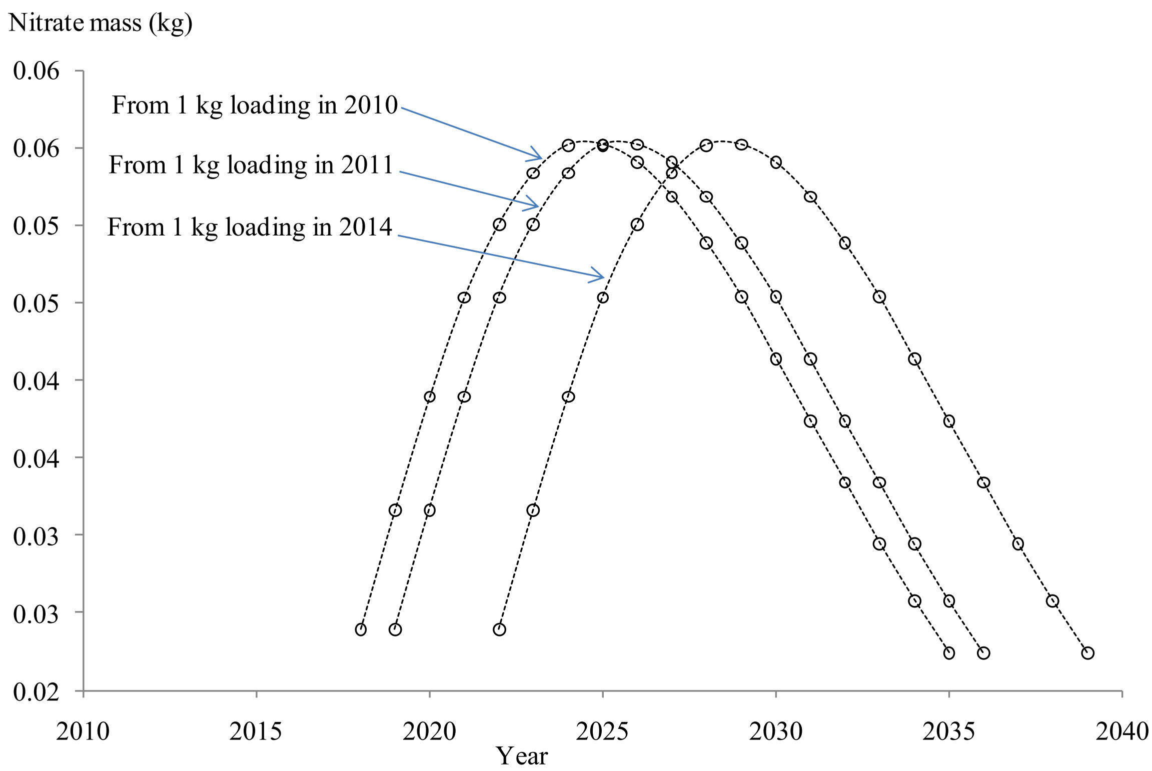

Figure 6.1: Response profiles under steady-state conditions.

Based on the above principle, if the groundwater flow system is in a steady state, the temporal increases in nitrate level caused by a unit (1 kg/year) loading during any year or during any number of consecutive years can be calculated from a single set of coefficients which measure the increases in nitrate level in each successive time period caused by a unit loading during a single time period. Thus the number of columns in the response matrix can be reduced to the number of sources (rather than number of sources × number of management periods).

Therefore, we re-define the response coefficients using the following indices.

f = farm: 1, 2, …, F.

r = receptor: 1,2, …, R.

d = delay (number of delayed time periods): 0, 1, …, D.

H_{frd} = increase in nitrate level that occurs at receptor r, d periods after unit (1 kg) nitrate loading in farm f during a single year, kg or mg/l. This is the response coefficient for source *f*, receptor *r*, and delay *d*. The structure of a typical transport matrix is shown in Figure 6.2.

		Farms			
		1	2 …		F
	1,0	H_{110}	H_{210}		H_{F10}
	1,1	H_{112}	H_{212}		H_{F12}
	…				
	1,D	H_{11D}	H_{21D}		H_{F1D}
Receptors × Delay periods	2,0	H_{120}	H_{220}		H_{F20}
	2,1	H_{122}	H_{222}		H_{F22}
	…				
	2,D	H_{12D}	H_{22D}		H_{F2D}
	…				
	R,0	H_{1R0}	H_{2R0}		H_{FR0}
	R,1	H_{1R2}	H_{2R2}		H_{FR2}
	…				
	R,D	H_{1RD}	H_{2RD}		H_{FRD}

Figure 6.2: Transport matrix.

Let the length of each time periods be one year. Then based on the definition of transport coefficients, and the assumption of linearity, if farm 1 loads 100 kg of nitrate into the aquifer underlying the farm in year 2010, the nitrate concentration or mass in receptor 2 would increase by $100\times H_{120}$ in the same year (2010), by $100\times H_{121}$ after a year (in 2011), and by $100\times H_{12D}$ after D years (in 2010+D). Similarly, if farm 1 loads 250 kg of nitrate into the aquifer underlying the farm in year 2011, nitrate concentration or mass in receptor 2 would increase by $250\times H_{120}$ in the same year (2011), by $250\times H_{121}$ after a year (in 2011), and by $250\times H_{12D}$ after D years (in 2011+D). Hence if farm 1 were given loading permits of 100 kg for 2010 and 250 kg for 2011, the farm could increase the nitrate concentration or mass at receptor 2 by up to $100\times H_{120}$ in 2010, $100\times H_{121} + 250\times H_{120}$ in 2011, …, and so on until year 2011+D.

6.5.3 Estimating Response Coefficients

Response coefficients may be estimated by observation or by simulation. The former is quite unrealistic in the case of groundwater nitrate transport, because, to estimate response coefficients from observation, one has to experiment and collect data for many years. Therefore, simulation is the best possible way to estimate the response coefficients, and reliable estimates may be achieved by calibrating the simulation models as data becomes available.

To obtain the two types of response coefficients required, we simulate one kilogram of nitrate loading from each farm. While there are many computer models suitable for the work, we use MT3D (Zheng, 1990) to simulate groundwater nitrate transport, together with MODFLOW (Harbaugh, Banta, Hill, & McDonald, 2000) to simulate groundwater flow.

We assume a fixed rate of water flow (recharge) from each farm to the aquifer (Fixed recharge means that recharge does not vary with the rate of mass nitrate leaching, but the flow rate may vary over the farms.). We assume a steady state groundwater flow regime, so the recharge and abstraction rates are constant over time, and hence the groundwater flow terms are constant over time. This is a commonly made assumption in applying the response matrix technique (Morgan and Everett, 2005). Based on these assumptions, we first simulate the groundwater flow system using MODFLOW. The groundwater flow file generated from the groundwater flow simulation is a major input file for the solute transport MT3D model.

Though the permits are defined in terms of mass nitrate loading, nitrate loading actually occurs via concentrated water percolating into the soil and leaching into the aquifer. MT3D allows specifying contaminant loading into the aquifer from such nonpoint sources as “recharge concentration.” To simulate 1 kg loading from each farm with MT3D, we assume that the rate of aquifer recharge (the volume of water that percolates into the aquifer per unit area of land, m^3/m^2) is known. Then we specify source loading as the concentration of recharge for the model cells (zone) which represent the aquifer below the source. The recharge concentration, equivalent to 1 kg of nitrate loading from each farm, is calculated as follows.

Ar_i = the area of farm I (m^2).

Rc_i = rate of aquifer recharge from farm I (m).

$None_i$ = set of model cells that represent farm i.

Cr_i = recharge concentration for $None_i$ which simulates 1 kg of nitrate loading from $None_i$, mg/l (g/m^3).

Assuming the loading is uniformly distributed over the whole area of the farm, the rate of loading from farm i is $1000/Ar_i$, g/m^2.

Cr_i = rate of mass loading / rate of recharge = $1000/(A_i \times Rc_i)$ g/m^3

In MT3D, we have to set the observation times to record the increase in concentration or mass in each successive time period. The simulation should be carried out until the nitrate mass loaded from the source passes all receptors, i.e., until the observed increases in nitrate concentration or mass tends to zero. Rather than setting the simulation period and number of observation time steps separately for each source, it is easier to set the simulation time to the maximum nitrate residence time in the catchment.

A simulation of 1 kg nitrate loading from farm f gives the response coefficients H_{frd} for all r and d. Therefore, we need F simulations to obtain the complete three-dimensional response matrix for F farms, M receptors, and D time periods.

The response coefficients are calculated assuming that the loading is equally distributed over the whole area of the farm. If the area of farm A is 10 ha, the trading system assumes that the loading rate is 50/10 = 5 kg/ha/year. It also assumes that loading occurs at a constant rate during the year. Accordingly, the monthly loading rate for farm A is 5/12 kg/ha/month. However, both the above assumptions are not limitations, because the transport coefficients can be calculated otherwise also. For example, if nitrate leaching from farms in the catchment occurs mostly in the winter months, then the transport coefficients may be obtained accordingly.

The tradable receptor capacities and the response coefficients are the basic parameter inputs for the trading system. They are used to model the water quality constraints which provide the basis for trading.

6.5.4 Water Quality Constraints

Tradable receptor capacities of each time period serve as the limiting factor in this trading system. The response coefficients indicate how the farms consume the capacity of the receptors. Using those parameters, we can formulate mathematical constraints to require the farms to collectively meet the capacity of receptors to accept nitrate. These constraints are usually known as water quality constraints or environmental constraints. They are a specific type of resource capacity constraints analogous to the capacity constraints applied in other markets (e.g., generator capacities in electricity markets). Hence we use the term "receptor capacity constraints" to refer to the constraints which require the sources to meet the tradable receptor capacities.

Define the following indices and parameters.

s = permit period: 1,…, S. The upcoming period is given by s =1. The last period for which the permits are traded is given by $s = S$. S is also the number of periods for which permits are traded.

t = monitoring period: 1,…, T. The upcoming period is given by $t = 1$. The last period for which the permits are traded is given by $t = T$. T is also the number of periods for which permits are traded. T>S.

Assume that the delay periods, permit periods, and monitoring periods are of the same length (for example, one year periods).

Let C_{rt} be the tradable capacity of receptor r in period t, kg or mg/l; and q_{is} be the size of the loading permit for period s (period-s permit) allocated to farm f after trade.

Under the assumptions above, if farm f load q_{fs} kg of nitrate into the aquifer during year s, then for all $t \geq s$ the nitrate concentration or mass at receptor r would increase by $H_{fr(t-s)}$. By using the loading permits allocated, the farms can jointly increase the nitrate level at receptor r in period t by $\sum_f \sum_s H_{fr(t-s)} q_{fs}$. In order to meet receptor capacities, the total nitrate mass or concentration jointly caused by all farms should not exceed the tradable receptor capacity of any receptor in any monitoring period. Assuming that nitrate does not accumulate at any receptor (i.e., if nitrate does not reside in any receptor more than one period)[16], the receptor capacity constraints are modelled as follows.

$\sum_f \sum_s H_{fr(t-s)} q_{fs} \leq C_{rt}$ for all r and t.

These water quality constraints are imposed at each monitoring period t. Related to the time frame of trading, three questions are to be answered: what is the length of each time period considered in the model, for how many time periods ahead should permits be allocated (S), and for how many time periods ahead should water quality constraints be imposed (T). T is also the maximum number of time periods considered in the model and is usually called the planning horizon. These are inter-related and inter-dependent decisions.

6.6 Time Frames of Trading

The trading program can have a single standard time period as a unit of measuring time so that the delay periods for which response coefficients are obtained, permit periods for which permits are allocated, and monitoring periods for which capacity constraints are imposed are of the same length. However, all time periods being equally long is not a requirement, they may be otherwise, for example, loading permits may be allocated for five year periods (valid for five consecutive years) and capacity constraints may be imposed every year. Capacity constraints may be imposed at time intervals of different length. For example, capacity constraints may be imposed for every year until a certain point, and for every ten years thereafter.

[16] If nitrate could reside in a receptor for more than a year, additional constraints are required to describe and restrict pollutant accumulation in the receptor. In Chapter 7, we discuss methods to deal with such situations.

However, it is simpler and possible to have equally long time periods so that the trading system has a single measure of time.

6.6.1 Length of the Model Time Steps

The length of each time period in the model is mainly determined by the goals of the trading program. Generally, water quality standards should be met continuously throughout the planning horizon. This is achieved by imposing water quality standards (as capacity constraints) at discrete time intervals. The time interval may be a day, a month, a year, or a decade. However, a few things must be considered in selecting the length of the time periods.

First, the length of each time period should be short enough to guarantee that the quality standards are met continuously, and long enough to avoid a large number of redundant water quality constraints in the mathematical programs used to clear the market.

Second, as the water quality constraints are set for each time period, the length of the time periods should be consistent with available water quality standards. For large water bodies such as Lake Taupo, the environmental authorities have set sustainable nitrate loading levels on an annual basis rather than on a monthly or daily basis. Therefore, it is preferable to have annual time periods in the trading programs.

Third, the problem will be simpler if the model time period is selected so that it is possible to set the permit period (length of time during which any permit is valid) equal to one or a few time periods. Commercial farmers may need permits to be valid at least for a year, because they usually plan for long-term, and farm land uses are not frequently altered.

Fourth, the physical characteristics of the groundwater solute transport system determine how fast the status changes and how often monitoring is required. Usually, in groundwater systems, the effects of external stresses do not appear quickly.

Taking the above considerations into account, we set the length of the modelling time period to one year. The trading system is designed to achieve the mass nitrate intake capacities of the receptors on an annual basis and the nitrate concentration based capacities of the receptors on an end-of-the-year basis. Therefore, the response coefficients are required for every year. The permits will also be allocated on an annual basis.

6.6.2 For How Many Periods Should Permits Be Allocated?

At a time of trading, permits may be allocated only for the current period ($s = 1$), for a few periods ahead ($s = 1, 2, \ldots, S \leq T$), or for all T periods ahead ($s = 1, 2, \ldots, T$). The decision has environmental, economic, and political implications.

Land uses which require huge capital commitments will be risky if the investors are uncertain about the availability of sufficient permits to cover their operations in the future. Therefore, farms would prefer to buy permits for more periods (S to be large).

Permits are allocated subject to future constraints, but these constraints are formulated from uncertain parameters. Both the response coefficients and tradable capacities are estimated values, and the actual nitrate transport profiles and available receptor capacities may vary from the estimates. Under such uncertainty, it may be wise to adopt a "wait-and-see" policy of allocating permits only for a few immediate periods, updating the models through learning, and allocating gradually into the future.

Countries have various regulations governing environmental resource allocations and those regulations may restrict the length of time for which permits can be allocated. The Resource Management Act (RMA 1991) is the governing legislation which specifies the rules regarding the allocation of resource consents[17] in New Zealand. Under the RMA, the duration of a loading permit may vary between 5 and 35 years. The permits are issued by the regional environmental authorities who set the duration within RMA limits. These regulations would also affect the decision on the number of years for which permits are allocated.

The permit structure designed in this work is not consistent with New Zealand's RMA regulations as we consider permits valid for a single year only. However, the proposed

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[17] In New Zealand, rights to use environmental resources are called consents rather than permits, and a nitrate loading permit is usually known as consent to discharge nitrate into groundwater.

mechanism provides more flexibility, as the farmers can buy permits for as many years as required within the market limits. To deal with the consents allocated under the RMA, we may consider the consents as an initial paper right which is adjusted annually (as discussed in Chapter 10).

The right number of years for which permits should be allocated is a compromise of the above conflicting environmental, political, and economic concerns. In most parts of this work, we assume that permits are allocated for five years ahead of the current period. The number is somewhat arbitrary, and the trading system can deal with any number of permit periods. In Chapters 10 and 11, we demonstrate how the number of permit periods would affect the performance of the trading program.

6.6.3 Planning Horizon

Nitrate loading in a single present period affects receptors over many future time periods. The question is, at any time trading takes place, how far have we to look forward into the future (how many future periods should be considered)? Ideally, a market should look forward as far as the impacts of traded permits extend. We call this period the "planning horizon."

We can find the maximum possible travel (delay) time D^R years that nitrate loaded from any point or farm in the catchment would take to pass all the receptors; this is the maximum nitrate residence time in groundwater[18]. Hydrologists usually estimate the maximum nitrate residence time as a tail percentile such as 99th or 95th, because the nitrate transport profiles (as shown in Figure 5.5) usually have long skewed tails. We can find D^R from available hydro-geological data on the catchment or by using a groundwater solute transport simulation. Then, response coefficients can be obtained for $D = D^R$ time periods. Theoretically, D^R is such that, for all $d \leq D^R$, at least one response coefficient $H_{frd} > 0$ exists, and for all $d > D^R$, all response coefficients $H_{frd} = 0$.

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[18] We assume that the main water body towards which the catchment drains is considered as a receptor (as we have recommended in section 6.1.3). If only groundwater monitoring receptors were selected, T^R may be less than the maximum nitrate residence time. In any case, T^R cannot be greater than the maximum residence time.

In large catchments, D^R may be many decades, e.g., 200 years in the Lake Rotorua catchment of New Zealand (Lock and Kerr 2008). Hence, for a tradable permit program, a workable estimate of D^R may be used ($D = \mathrm{D}^R$ such that $H_{frd} \geq \delta \approx 0$ for all $t \leq D^R$ and $H_{frd} < \delta$, for all $d > D^R$), ignoring the tail effects.

We discussed how to set D, the maximum delay time for which response coefficients are required, not the planning horizon T. We suggest that the correct planning horizon for a trading system is $T = S+D$ years, i.e., D years from the last year for which permits are allocated. If we selected a planning horizon $T < S+D$, nitrates loaded from some farms may reach a receptor in year $T+1$, year $T+2,\ldots$, or year $S+D$ and these farms and their impacts will not be taken into account. As a consequence, the trading schema becomes unable to meet the nitrate intake capacities after T years.

The planning horizon $T = S+D$ is a generally feasible solution which is physically correct, capable of achieving long run water quality goals, and is fair in that every farm would be priced to pay for all their impacts on all receptors over time. However, a rational economic entity or an investor may not like to compromise current economic benefits to avoid some environmental damage that is expected to occur after many decades, because the uncertainly is high. Hence, the stakeholders may oppose a planning horizon of 50+ years. In Chapter 10, we will show that depending on the distribution of response coefficients (i.e., the catchment hydrogeology), and the current concentration distribution in groundwater, the length of the planning horizon can be reduced (below $S+D$) without compromising the environmental goals.

6.7 Market Design and Operation

The market is designed to operate as a periodic auction[19] which uses an LP to find the optimal permit allocations and prices. The farms will be able to buy permits from the auction which takes place at the beginning of every trading year. To buy and sell

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[19] We use the word "auction", but unlike many other auctions, the proposed market is not (always) an iterative process by which an equilibrium price is found.

permits, the farms have to submit bids indicating how much they are willing to pay (or accept) for loading permits.

6.7.1 Market Type: Gross Pool or Nett Pool[20]?

The proposed market operates as a gross pool market which requires the participants to bid for quantities starting from zero, ignoring any initial permit holdings. The participants bid prices for a set of quantity tranches. The maximum number of bid tranches is fixed, but the participants can choose the size of each tranche. For example, Farm1 may submit five bids as 60 kg @ $20, 40 kg @ $12, 70 kg @ $6, 80 kg @ $2, and 50 kg @ $1. Based on the theory of diminishing marginal utility, the bids mean that this farmer would pay $20/kg for the first 60 kg of nitrate loading, $12/kg each for the next 40 kg of loading and so on. If another farm (Farm 2) which already owns a permit of 250 kg has submitted the above bids, the bids mean that it would sell 80 kg if the price is $2/kg or above, another 70 kg if the price is $6/kg or above and so on. The five bid tranches are given as a bid function in Figure 6.3.

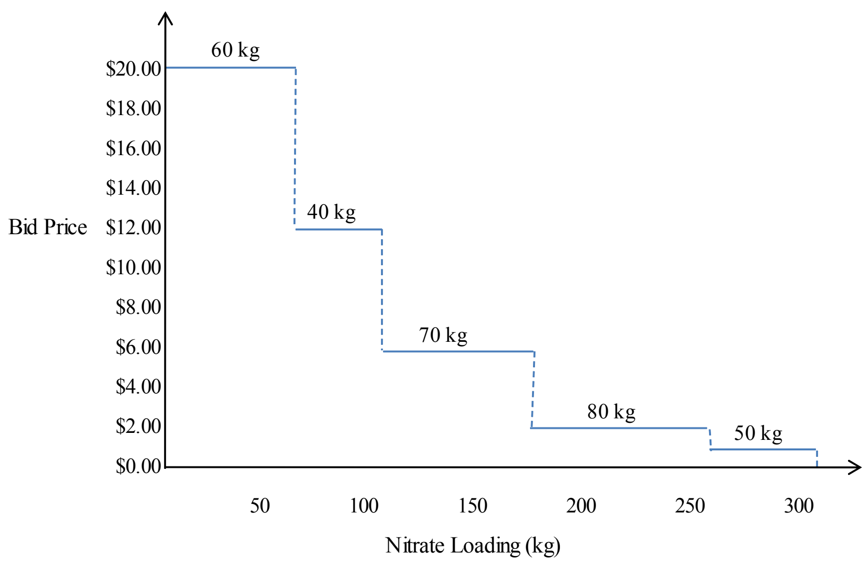

Figure 6.3: Shape of the bid Functions.

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[20] The material discussed about gross pool and net pool markets and LP formulations was obtained from Raffensperger (2009)and personal communication with E. Grant Read.

A gross pool market does not accept sell offers. A participant who already has a permit and is willing to sell if the price is high enough, has to submit the offer as a gross poll bid rather than an offer. For example, if Farm 3 which currently has a permit of 100 kg is willing to sell 30 kg of it at $20/kg, the remaining 70 kg at $1000/kg, and is willing to buy another 50 kg at $8/kg, its gross pool bids should be 70 kg @ $1000, 30 kg @ $20, and 50 kg @ $8.

After clearing the market, the net purchases or sales are calculated from the difference between the quantity cleared and the initial position. For example, if the permit prices as determined by the LP solution were $10, $20, and $10 per kg for farms 1, 2, and 3 respectively[21], then Farm 1 will be buying by 100 kg at $10, Farm 2 will be selling all of its 250 kg at $20, and Farm 3 will not buy or sell any.

Gross pool market operations may be difficult to understand from the participant's point of view. Alternatively, the market may operate as a net pool market which allows the participants to submit bids to add to the initial position and offers to sell from the initial holdings. Net pool operation is easy to understand. The market may operate either way, because net pool bids and offers can be easily transformed into gross pool bids and vice-versa if the initial positions are known. Following the popular electricity market example, we design a gross pool market, which is consistent with the gross pool LP formulation used to clear the market (discussed in Chapter 7).

All the farms in a catchment are assumed to be participating in the trading system. The farms that do not actually participate in the market by submitting bids, are assigned two default bid tranches: one with a price of infinity (a relatively large value) and a quantity equal to the initial position, and the other with price zero. These two default bids indicate that the farm does not wish to either buy or sell.

[21] Prices assigned to each farm can vary depending on their locations. In Chapter 7, we discuss how to set the prices.

If the farms wish to buy future permits, they have to bid indicating how much they are willing to pay now (discounted present value), because all payments are settled immediately, once the market is cleared.

6.7.2 Market Regulation

A government authorized institution (possibly a regional environmental authority that is responsible for monitoring and controlling water pollution in the catchment) should oversee the trading system. We use the term “market authority” to refer to this institution[22].

At implementation, the responsibilities of the market authority include collecting and maintaining all data and information required, setting up the trading program, developing the physical simulation models, authenticating and calibrating the models, setting receptor capacities, specifying the trading and settlement procedures, and initiating any required corrections or improvements.

The operational responsibilities include calling for bids, clearing the market, settling payments, and regulating the permits via monitoring and enforcement. The market authority may hire an independent entity to carry out market operations. We use the term “market operator” to refer to the institution which operates the trading system.

6.7.3 Market Clearing Procedure

Once the farms have submitted their bids, the market operator uses the LP to clear the market. The bids provide objective function coefficients for the market-clearing LP. The LP solution produces market-clearing commodity prices, locational permit prices and optimal allocations. The market operator then calculates the net trades from the initial (pre-trade) and optimal (ex-post) permit positions, collects money from net buyers, pays net sellers, and clears the market. All payments, including the payments

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[22] A regional environmental authority’s roles as the “regulator” who owns the environment on behalf of the public and as the “market authority” who oversees the trading program are different. So the same government institution may have different independent roles in the trading program.

for future permits traded, are cleared immediately. Some trial market rounds would provide price signals to the farms so that they can adjust the bids accordingly.

6.7.4 Monitoring and Enforcement

Once the market is cleared for some trading year, all the participants should comply with the cleared permit positions until the next auction. The market authority should oversee the trading system and enforce the loading limits specified by the permits.

Monitoring devices may be located in the farms to measure the nitrate concentration in the leachate and thus the actual loading. However, it is not possible to measure the actual loading from the farms during a year with 100% accuracy.

The amount of nitrate loading is determined by the type of land use (Chapter 9). Instead of monitoring the quantitative loading, the environmental authorities may restrict the farms to the land use practices allowed by the size of the loading permit held. Better monitoring may be achieved via a combination of the above two monitoring methods.

6.7.5 Online Trading

Such a trading system is best implemented as an online trading system (although this is not a requirement) so that the farms can trade multilaterally in a virtual market place. An official web site will coordinate all transactions. The participants will log into the trading system web page and submit bids online. After solving the LP with the set of outstanding bids, the market operator can post the prices and quantities cleared on the auction web which facilitate online transactions.

The electronic auction should authenticate participants at login and accept bids. Access to information should be customised, so that everyone can view public information such as trade history and prices, but not private information such as other traders' pending bids. Bids can be stored in a database, along with other relevant information such as each land user's details and initial allocations. The market operator should have administrative rights and be capable of clearing the market and posting the cleared quantities and prices on the web page. The tools available for the farms to optimise their own bids (Chapter 9) can be linked to the online trading system.

Despite the complexity of actual market operations, the user interface can provide a simplified, understandable picture of the market and its operation. Since a gross pool market is difficult to understand, the users should be allowed to submit either a set of gross pool bids or net pool bids and offers. Users may also specify the size of the permits in different units: in kg or in kg/ha/year. Such facilities can be provided through the interface. When the market operator initiates market clearing, a computer algorithm would convert all inputs into the specific format used in the LP. After clearing the market, the prices and allocations should be available in user friendly formats.

In this chapter, we discussed the structure and architecture of the proposed market mechanism. We mentioned both necessary and preferential features. The basic idea is using an LP to find the optimal prices and allocations. We discussed how to define the permits and how to use available data, tools and techniques to estimate the parameters required for the LP models. In the next chapter, we present alternative LP models to be used for market clearing under different hydro-geological and socio-economic conditions.

Chapter 7

7 LP MODELS FOR PRICING NITRATE LOADING PERMITS[23]

7.1 Introduction

The proposed market mechanism enables the farms to trade nitrate loading permits in an ex-ante market (possibly in a year-ahead market). The mechanism requires the market operator to find the equilibrium prices ex-ante. As in many electricity markets, an LP is used to determine the optimal quantities and prices, the size of each year-*s* permit allocated to each farm, and the price of each year-*s* permit assigned to each farm. The LP is formulated to maximise benefits from trade subject to the water quality constraints. Objective function coefficients are obtained from the bid prices. Response coefficients and tradable capacities are exogenous parameters which describe the underlying physical system and thus the physical constraints. Clearing the market means solving the LP with a set of bids submitted by the participants. The LP solution gives the prices and final permit positions for each farm. The prices charged to the market are obtained from the shadow prices of the model constraints.

This chapter is about modelling the LP and deriving the prices and allocations. To serve as a base case, we first present a basic LP which models the essentials of a

[23] This chapter is based on Prabodanie et al. (2010).

nitrate permit market. After discussing the limitations of the basic model, we present different types of relevant constraints, how to model them in a generally applicable market-clearing LP, and a how they affect market prices. Based on the theory of nodal pricing applied in electricity markets, we interpret and explain the prices and allocations; and describe the price structures and relationships. For this purpose, we drew up ideas from Ring (1995), who presented a dispatch-based pricing model for electricity markets. We describe the settlement process, revenue distribution, and gains from trade, assuming no previously allocated permanent or long term loading rights.

7.2 Optimal Loading (Basic) Model

In this section, we present a *basic* LP which models the *essentials* of a market in diffuse nitrate discharge permits. The basic model provides a foundation for the development of more detailed general models.

Indices:

f = farm: 1,…, F.

r = receptor: 1,…, R.

d = delay (travel time) in years: 0,…, D. D is the maximum nitrate travel time (residence time) in the catchment.

s = permit year: 1,…, S. The upcoming year is given by s =1. The last year for which the permits are traded is given by s=S. S is also the number of years for which permits are traded.

t = monitoring year: 1,…, S+D. The upcoming year is given by t = 1.

Rather than expressing s and t relative to the upcoming year, we may express them in terms of the absolute year, for example, as 2011,…, 2014. If the upcoming year is $\hat{S}$, the permit year $s = \hat{S},\ldots, \hat{S}+S-1$ and the monitoring year $t = \hat{S},\ldots, \hat{S}+S-1+D$.

k = bid tranche: 1,…, K.

Parameters:

H_{frd}= increase in nitrate level that occurs at receptor r, d years after unit (1 kg) nitrate loading in farm f during a single year, kg or mg/l.

C_{rt} = tradable nitrate intake capacity of receptor r in year t, kg or mg/l.

U_{fsk} = quantity specified in bid tranche k submitted by farm f for year-s permits, kg.

P_{fsk} = bid price specified in bid tranche k submitted by farm f for year-s permits, \$/kg.

Decision variables:

x_{fsk} = quantity accepted from bid tranche k submitted by farm f for year-s permits, kg.

q_{fs} = size of the year-s permit allocated to farm f after trade; this is the maximum loading allowed for farm f during year s, kg.

Model: OLM

Maximize $\sum_f\sum_s\sum_k P_{fsk}x_{fsk}$, subject to:

Upper and lower bounds on bid tranches

$x_{fsk} \leq U_{fsk}$ for all f, s, and k. (P-1) θ^+_{fsk}

$-x_{fsk} \leq 0$ for all f, s, and k. (P-2) θ^-_{fsk}

Calculation of final permit positions

$\sum_k x_{fsk} - q_{fs} = 0$ for all f and s. (P-3) μ_{fs}

Receptor capacity constraints

$\sum_f \sum_{s=\max(1,t-D)}^{\min(t,S)} H_{fr(t-s)} q_{fs} \leq C_{rt}$ for all r and t. (P-4) λ_{rt}

The LP is formulated as a gross pool market which is independent from the initial distribution of permits. The traded quantities should be calculated from the difference between the initial position and the optimal position obtained from the LP solution. A simplified form of the above LP may be given as follows. Since all the parameters are non-negative, the LP is always feasible.

Maximize $\sum_f\sum_s\sum_k P_{fsk}x_{fsk}$, subject to:

$\sum_f \sum_{s=\max(1,t-D)}^{\min(t,S)} H_{fr(t-s)} \sum_k x_{fsk} \leq C_{rt}$ for all r and t.

$0 \leq x_{fsk} \leq U_{fsk}$ for all f, s, and k.

7.2.1 Objective Function

The objective function coefficients P_{fsk} indicate how much each block of nitrate loading is worth to the bidder, the price each farm would pay (or accept) for each incremental block of quantity, starting from zero. Hence, the objective function which maximises the sum of P_{fsk} multiplied by x_{fsk} essentially maximizes the total benefits from trade.

A rational farm would buy another X units of loading permits if the incremental profit from each unit is above the price, and therefore bid to buy at the marginal profit[24]. Thus, the bids indicating the additional quantity preferred at each price step correspond to a piece-wise linear marginal profit function of the farm. Hence, if the bids indicate the true economic contributions of the farms, the objective function also maximizes the true social benefit[25].

We do not use time discounts in the market clearing model, relying on the farms to discount their bids at their own rates. Hence, the bids for future permits should indicate the discounted present value of the future permits, based on each farm's own private discount rate.

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[24] If the market is not perfectly competitive, the buyers and sellers could game the bids above or below the marginal profit to affect market prices. However, a catchment usually has a relatively large number of farms and a catchment scale market is expected to be workably competitive.

[25] Markets in pollution permits are usually modelled to minimise abatement cost rather than to maximise profit (Montgomery 1972; McGartland 1988; Ermoliev et al. 2000). However, allocation of diffuse nitrate discharge permits is a problem of optimising the allocation of land uses rather than the abatement responsibilities. In the case of nitrate loading permits, forgone profit from a more nitrate intensive farming option may be considered as an abatement cost. Therefore, maximising profit is the same as minimising abatement cost.

7.2.2 Constraints

The quantity accepted in each bid tranche cannot be negative (P-2), while upper bounds on bid tranches (P-1) ensure that it does not exceed the maximum quantity at that bid price specified by the bidder. The final position of each year-s permit for each farm f is calculated (P-3) as the sum of the quantities accepted from the farm's bids for year-s permits.

Markets in nitrate loading permits should necessarily include constraints that require the market to meet the maximum acceptable nitrate mass or concentration at each receptor in each time period. As mentioned in the previous chapter, we refer to these essential constraints as receptor capacity constraints (P-4).

The variables listed to the right of the constraints are the associated shadow prices (dual variables). The dual formulation of the problem provides insight into the commodity prices that match the demand and supply.

7.2.3 Dual Formulation and Shadow Prices

While the OLM models the resource allocation problem, the dual of the OLM models the resource valuation problem. In the following dual formulation, the primal variables associated with the dual constraints are listed to the right of the constraints.

Minimise $\sum_f \sum_s \sum_k U_{fsk} \theta^+_{fsk} + \sum_r \sum_t C_{rt} \lambda_{rt}$, subject to:

$\theta^+_{fsk} - \theta^-_{fsk} + \mu_{fs} = P_{fsk}$ for all f, s, and k. (D-1) x_{fsk}

$-\mu_{fs} + \sum_r \sum_{t=s}^{s+D} H_{fr(t-s)} \lambda_{rt} = 0$ for all f and s. (D-2) q_{fs}

μ_{fs} free for all f and s.

$\lambda_{rt} \geq 0$ for all r and t.

θ^+_{fsk} and $\theta^-_{fsk} \geq 0$ for all f, s, and k.

The shadow price λ_{rt} of the receptor capacity constraint (P-4) for some r and t indicates how much the benefit-maximising objective function would increase if the nitrate intake capacity of receptor r in time period t were increased by one unit. Farms would make an incremental profit of λ_{rt} if they were allowed to increase the nitrate level at receptor r in time period t by one kg or mg/l. To stop the farms doing so, they should be charged at λ_{rt} per unit increase in nitrate mass or concentration at receptor r in period t. If the bids are truthful, λ_{rt} is a true marginal cost based price which results in efficient allocation of the receptor capacities. Regardless of whether the bids indicate the true marginal profit functions, λ_{rt} is a market price which matches the demand and supply, maximising the benefits from trade.

As λ_{rt} is the *current* market price of the capacity of receptor r in time period t, we call it a "receptor capacity price," the price for increasing the nitrate level at receptor r in time period t. As a loading permit is equivalent to a bundle of receptor capacity rights, the price that should be charged from (or paid to) any farm per each 1 kg of loading permit bought (or sold) can be derived from the prices of the receptor capacity rights in the bundle as $\sum_r \sum_{t=s}^{s+D} H_{fr(t-s)} \lambda_{rt}$.

Even if the ability of a receptor to accept and dilute nitrate is constant over the years (for example, 400 tonnes in any year), the tradable capacities, and thus the associated receptor capacity prices, may vary over time due to the temporal variations in non-tradable sources. For example, a huge plume of nitrate already in the aquifer may be flowing towards the receptor and expected to reach the receptor after another 20 years. Then the tradable resource capacities of the years after the 20th (C_{r21}, C_{r22}, …) will be lower and the associated capacity prices are likely to be higher.

Demand for the resources varies depending on the farm locations and their individual characteristics. For example, if most of the farms are far upstream, having longer delay times, the demand for the capacity of later years may be greater than the demand for earlier years, particularly if they have already been operating in an unconstrained way for some time. Hence the (undiscounted) price for the capacity of later years may be greater than the price for capacity in earlier years.

The shadow price μ_{fs} of the constraint (P-3) which calculates the final year-s permit position of farms f indicates how much the objective function would increase if farm f were given another 1 kg of year-s permits. Unlike the receptor prices (λ_{rt}) which describe the market equilibrium in receptor capacity rights, μ_{fs} is indexed to a particular farm, and it describes the economic characteristics of the farm. Therefore, we call μ_{fs} the "participant price". Since the farms have a specific location in the catchment, the participant prices are similar to the "nodal" or locational prices used in electricity markets. For this simple formulation, these prices could be described as "market clearing prices". But they have not been derived from strictly locational demand and supply balance constraints and, as discussed in section 7.4.3, they may be affected by private constraints.

The shadow price θ^{+}_{fsk} of the bid upper bound constraint (P-1) indicates how much the social benefit would increase if farm f would utilize another 1 kg at the marginal price P_{fsk} (i.e., if farm f could offer to buy another 1 kg at price P_{fsk}). If the k^{th} bid of farm f corresponds to some land use option[26], then θ^{+}_{fsk} is the value of expanding that land use (in terms of fertilizer application rate, area cultivated, stocking density, etc.) by another 1 kg nitrate loading. Hence, if the bid is accepted, $\theta^{+}_{fsk} > 0$. The shadow price θ^{-}_{fsk} of bid lower bound constraint (P-2) indicates how much the society would lose if one unit were accepted from that bid. Hence, if the bid is not accepted, $\theta^{-}_{fsk} > 0$.

7.2.4 Dual Constraints

The dual constraint (D-1) associated with the primal variable x_{fsk} describes the relationship between participant prices and bids (steps of the marginal profit functions) as $\mu_{fs} = P_{fsk} - \theta^{+}_{fsk} + \theta^{-}_{fsk}$. From duality and complementary slackness we can derive the following relationships.

If a bid is fully accepted, i.e., if $x_{fsk} = U_{fsk}$, then $\theta^{+}_{fsk} > 0$ and $\theta^{-}_{fsk} = 0$.

Therefore, $\mu_{fs} = P_{fsk} - \theta^{+}_{fsk}$.

If a bid is not accepted, i.e., if $x_{fsk} = 0$, then $\theta^{+}_{fsk} = 0$ and $\theta^{-}_{fsk} > 0$.

Therefore, $\mu_{fs} = P_{fsk} + \theta^{-}_{fsk}$.

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[26] The step tranches of the farm profit functions, and thus the bids, would possibly correspond to different land use options. Chapter 9 provides information about the relationships between the land uses and marginal profit functions and how the farms would choose the bids.

If a bid is partially accepted, i.e., if $0 < x_{fsk} < U_{fsk}$, then $\theta^{+}_{fsk} = 0$ and $\theta^{-}_{fsk} = 0$.

Therefore, $\mu_{fs} = P_{fsk}$.

Figure 7.1 provides a graphical view of the relationships. It indicates that the participant price is the dollar value at the point where the vertical line corresponding to quantity = q_{fs} intersects farm f's marginal profit function for year-s permits.

Hence, the price which rations the final permit allocation is the participant price. If the price charged or paid to each farm equals the participant price, the market allocation agrees with the price-quantity preferences indicated in the bids. In electricity market terminology, such an allocation is called a "merit order" allocation.

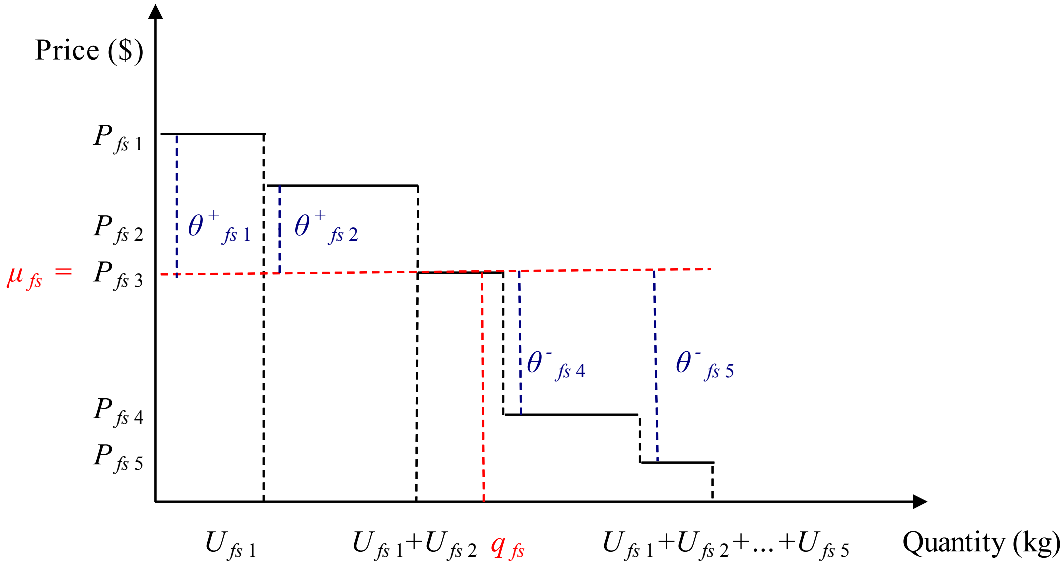

Figure 7.1: Participant prices and the bid functions.

The dual constraint (D-2) associated with the primal variable q_{fs} indicates that the participant price equals the market price per unit nitrate loading from farm f (or from the location of farm f) calculated from the receptor capacity prices. Hence, if the receptor capacities were the only limiting factor in the market (as in the above basic model), the participant price equals the market price of nitrate loading from the participant's location, and hence the market allocation always satisfies the participant preferences indicated in the bids. In the next sections, we discuss general situations in which participant prices can deviate from the market prices of locational loading.

7.2.5 Limitations of the Basic OLM

The basic OLM presented above has two major limitations. First, it models the essential receptor capacity constraints as the only factor which restricts nitrate loading from the farms and thus the permit allocations. However, catchment water systems may have other constraints. For example, the environmental authorities may impose temporary restrictions on total nitrate loading into highly polluted areas of the groundwater aquifer[27]. The farms may also have their own private limitations such as minimum operating levels. If any applicable constraint is ignored, the tradable permit system may fail to achieve the environmental goals.

Second, the basic OLM generates market prices for receptor capacity only. The market price of nitrate loading from any farm (location) can be calculated from the market capacity prices, but the model itself does not always provide *locational* prices which can be charged to the farms directly (as mentioned earlier, the participant price cannot always be considered as a market clearing price). A true locational price for nitrate loading should describe the social marginal cost of nitrate loading from the particular location, whatever the entity or entities operating in that location. And they should be consistent for all farms in a similar location. To obtain such market clearing prices, we have to separate the locational effects of nitrate loading and the effects of participants' private characteristics.

The next section discusses different types of applicable constraints, and about separating farms and locations; the following section presents how to model these constraints in a generalised LP which may be used for pricing and allocating nitrate loading permits in any catchment. We show how to upgrade the model so that it always generates locational loading permit prices which are similar to the nodal prices used in electricity markets.

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[27] A specified area of a groundwater aquifer may also be considered as a receptor, but estimating response coefficients and tradable capacities for such a receptor is difficult. Hence, constraints imposed temporarily to control nitrate loading into some area of the aquifer are not considered as receptor capacity constraints.

7.3 Generally Applicable Constraints

A market in nitrate loading permits can have two major types of constraints: (1) *market* constraints that describe the system of nitrate transport in groundwater and surface water, and the capacity of water bodies to accept nitrates, and (2) *private* constraints that describe the operational limitations of individual sources.

In the above basic market model, the nitrate transport system was described by the response coefficients. The ability of the water bodies to accept nitrates was described by the receptor capacity constraints (P-4), using the response coefficients. The receptor capacity constraints alone would sufficiently model the underlying physical system and its quality requirements if the selected receptors were reliable indicators of the overall water quality in the catchment, if the nitrate intake capacity of each receptor were specified on a yearly basis, if the receptors were completely independent from each other, and if nitrate did not reside at any receptor for more than a year, implying no carry forward to the next year. Large and hydro-geologically complex groundwater catchments do not necessarily satisfy all those conditions and therefore, additional environmental constraints may be required to describe the physical system and to model additional water quality requirements. We recognize two major types of applicable market constraints: *receptor constraints* specified in terms of nitrate levels at the receptors and *source constraints* imposed on nitrate loading from the sources (Private constraints are also related to individual sources, but we use the term source constraint to refer to non-private market constraints imposed on cumulative nitrate loading from multiple sources.)

7.3.1 Receptor Constraints

The receptor capacity constraints (P-4) require the market to meet the nitrate intake capacity of each receptor in each time period. They are clearly receptor constraints. Since we have already discussed them in detail, this section discusses additional types of receptor constraints.

Even if the receptors sufficiently represent the overall water quality in the catchment, the constraints on each receptor's nitrate intake capacity in each year alone may not model all the receptor-based water quality requirements, especially in the presence of multiple surface water receptors. Nitrate may take many years to travel through large receptors such as lakes, for example, water, and thus nitrate, entering into Lake Taupo in New Zealand may take 11 years to pass through the lake to the Waikato River (Morgenstern 2008). In such cases, multi-period constraints are required to restrict the cumulative effects over many consecutive years.

The environmental authorities of large catchments may select several connected receptors to maintain water quality in the sub-catchments (Figure 7.2). For example, in a river catchment with many sub-catchments draining to different river segments, the catchment authority may wish to control nitrate discharge into each segment (considered as one receptor) as well as the total discharge into the river (total discharge into all receptors). Such cases require multi-receptor constraints to control the aggregate effect over several receptors in a single time period.

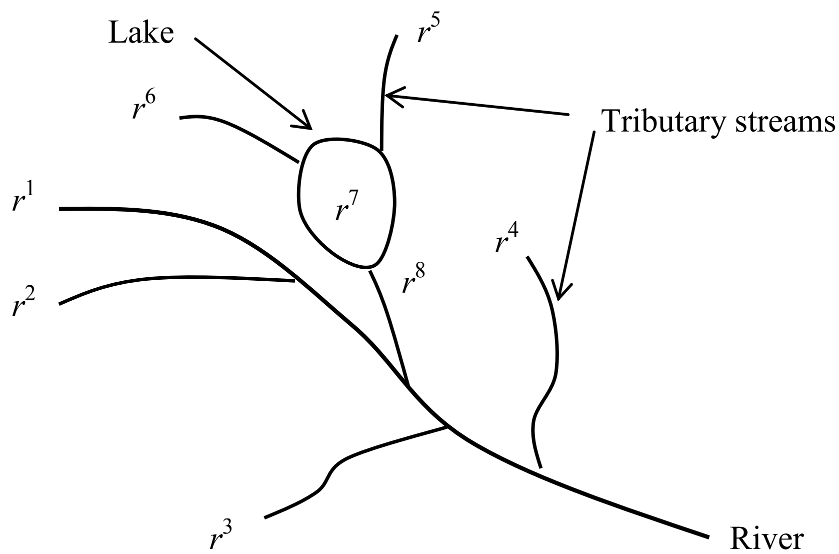

Figure 7.2: Connected receptors.

Both the multi-period and multi-receptor constraints discussed above are related to nitrate residence and transport in surface water receptors. Even though nitrate residence and transport in groundwater (and thus across groundwater receptors) are implicitly described by the response coefficients, the model does not have a representation of nitrate transport across surface water receptors. Hence, if the receptors are connected so that nitrate travels from one receptor to another, and/or if nitrate travel times (delay) in surface water receptors are significant, explicit representations of those physical transport systems are required for a proper market clearing model. However, including detailed mathematical models of nitrate fate and transport in surface water in the market clearing models can create extra complexity. The middle ground is to use some simplified linear approximations to describe the spatiotemporal effects of nitrate transport in surface water (such as the regression equations proposed by Ejah and Peralta (1995), discussed in Chapter 3).

Apart from the receptor capacity constraints, and the multi-receptor/period constraints that describe nitrate fate and transport in surface water, the environmental authorities may impose other multi-receptor/period constraints. Due to uncertainties in mixing and residence of nitrate in slow moving water bodies such as lakes, and fluctuations in water quantity, the environmental authorities cannot rely only on either a restriction on cumulative discharge over many periods or independent restrictions on the discharges in each period. Hence, a workable solution is imposing relatively relaxed limits on the effects in each time period together with a stringent limit on cumulative effects (for example, if the nitrate intake capacity and maximum nitrate residence time in a lake are roughly given as 40-50 tonnes/year and five years, a restriction of a 50 kg nitrate load in each year together with a restriction of 200=40×5 tonnes aggregate over any five consecutive years). Such constraints give also more flexibility to the permit users in scheduling their operations.

7.3.2 Source Constraints

Imposing water quality standards at a few receptors alone may not be sufficient to guarantee local groundwater quality. On the other hand, it is difficult in practice to monitor a large number of receptors. Therefore, environmental authorities may impose source based constraints as caps on nitrate loading. Loading caps may be imposed on individual loading rates, regional totals, catchment totals, or on the total loading from any defined geographic area within the catchment[28]. Usually, regional

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[28] For example, an area covered by a circle drawn around a lake (a ring), or a rectangular area along the side of a stream.

loading caps are used to control local groundwater nitrate concentration, because imposing regional caps is simpler and easier than having a large number of groundwater receptors[29].

If a loading limit affects many farms competing for nitrate loading permits, the market models should include the constraint, but if it affects only one farm, the constraint may be imposed outside the market, requiring the farm to meet the restriction regardless of the size of the permit held. For example, under the US sulphur dioxide trading program, each utility has to meet the federal emission standards regardless of the size of the emission permit held (Schary & Fisher-Vanden, 2004). Similarly, a uniform standard on per hectare loading rate can be imposed outside the market to avoid or reduce the number of source based constraints in the market. However, the inefficiencies resulting from such uniform standards are well known (Ragan, 2001). The complexities arise from having many source based constraints in the market clearing models, and methods to deal with them are discussed in section 7.5.

7.3.3 Private Constraints

The basis OLM presented above assumes that all demand side private constraints are internalized into the bids. However, the farms may have some private constraints, which they cannot easily internalize into their bids. Some common examples are inter-temporal constraints and minimum permit requirements.

A farm may need the same quantity for the next 10 years, or a farm may not need more than 200 kg in total over the next two years because if much fertilizer is applied on the farm this year, the fertility may remain without need for applying that much fertilizer in the next year. It is difficult to internalise such inter-temporal constraints into bids submitted for each year separately. Trial market rounds would help the farms

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[29] Loading caps can be modelled as receptor constraints assuming the whole aquifer or a defined area of the aquifer as a receptor in which the mass nitrate level is monitored and controlled. However, confusions can arise in defining response coefficients for such receptors. Hence, we model the loading caps as source constraints imposed directly on source loading, rather than as receptor constraints.

to iterate towards a set of bids which meet the additional constraints, but this may need a large number of trials.

The farms may also have minimum permit requirements such as “I need at least 50 kg or none otherwise”, because crop and livestock farms will not be economical below a certain scale. Therefore, to continue farming, the farms may need a permit to cover the minimum possible discharges.

Some electricity markets allow the participants to impose additional conditions such as non-divisible quantity bids, start-up costs, and ramp rates on the quantity/price bids (Contreras, Candiles, Fuente, & Gomez, 2001). Similarly, the market authorities may allow the farms to submit additional conditions such as minimum permit sizes and inter-temporal constraints.

Private inter-temporal constraints can be included in the market models as constraints imposed on individual allocations. Such private constraints may provide space for strategic price manipulations (Oren & Ross, 2004), but such manipulation is equally possible in principle by manipulating simple offers over multiple market rounds. Conversely, private constraints can provide more flexibility to the market, in choosing solutions that are feasible and acceptable to permit users, thus avoiding the need for many market rounds. Provided the private constraints form a convex LP feasible region, the model can still generate efficient market prices for the bids submitted.

However, conditions such as minimum permit requirements and non-divisible bids may lead to non-convexities too (Bjørndal and Jörnsten 2008). Therefore, at this stage, we do not include any private constraint that requires integer variables in the market clearing models, assuming that the farms can internalize those constraints into their bids based on past learning, or by iterating through trial market rounds. In Chapter 12, we discuss some methods to deal with such non-convexities in permit markets.

7.3.4 Side Constraints

Apart from the physical and private constraints discussed above, the market-clearing LP models may include restrictions such as the maximum total permit allocation to the farms having some specific characteristic (for example, the dairy farms or effluent irrigation farms). Even though such constraints stem from the institutional level, they are not related to the underlying nitrate transport system or the ability of the water bodies to accept nitrate, and even though such constraints are related to private characteristics of the farms, they are not private because they are imposed by the institutional level. Therefore, we call such constraints "side constraints."

7.4 Separation of Locational Loading and Permit Allocations

The receptor and source based (market) constraints discussed above restrict the locational nitrate loading (the quantity of nitrate that goes into the groundwater system), regardless of whose nitrate that was[30]. In contrast, the private and side constraints restrict individual permit allocations, regardless of the location, and then nitrate loading indirectly. Locational prices should be derived from the constraints which restrict locational loading, but not those which describe private restrictions and limit individual allocations. Therefore, a proper market model should separate the locational loading and individual permit allocations to produce truly locational prices.

There are two ways to separate the location of nitrate loading and the private characteristics of the market participants. One method is to define a set of locations or nodes, $n = 1,\dots, N$, to obtain response coefficients H_{nrt} for each node rather than for each participant, and assigning each participant to a node. A clearer market model would calculate the total loading at each node using a variable q^{nodal}_{ns} for each node as $q^{nodal}_{ns} = \sum_{f\in n} q_{fs}$. Then the receptor and source based (market) constraints can be imposed on nodal loading variables and private and side constraints can be imposed on individual allocations to produce nodal prices which match nodal demand and supply.

Another method is to define two separate variables for permit allocation to each farm and net nitrate loading from each farm location, q_{fs} and q^{load}_{fs} respectively. We can

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[30] These market constraints are analogues to the constraints which restrict the net nodal electricity injection into the transmission networks, mainly the physical limits of the transmission network. They restrict the net injection from the nodes, whatever the entities operating in the affected nodes.

then impose the receptor and source constraints on locational loadings $q^{load}{}_{fs}$, and private and side constraints on permit allocations q_{fs}.

Since the former method has the additional advantage of being able to group the adjacent small farms into one node, and eliminate repetitions in the response matrix, we use the first method.

Using the nodal loading variables, all receptor and source based (market) constraints, including the receptor capacity constraints, can be modelled in the general form as $\sum_n\sum_s A_{ns}q^{nodal}{}_{ns} \leq V$, where V and A_{ns} are some constants. However, to recognize the price structures and relationships, the receptor capacity constraints, multi receptor/period constraints, and source loading constraints should be separately specified.

We can separately specify the receptor constraints using a receptor end variable y_{rt} defined as the total allocation of receptor capacity[31], for each receptor and time period so that $y_{rt} = \sum_f \sum_{s=\max(1,t-T)}^{\min(t,S)} H_{nr(t-s)} q^{nodal}{}_{ns}$. Then the receptor capacity constraints can be specified directly as $y_{rt} \leq C_{rt}$, and the multi-receptor/period constraints can be formulated as $\sum_r\sum_t B_{rt}y_{rt} \leq W$, where W and B_{rt} are some constants. Source constraints can be specified as $\sum_n\sum_s A_{ns}q^{nodal}{}_{ns} \leq V$. Private constraints can be modelled as $\sum_f\sum_s E_{fs}q_{fs} \leq Z$, where Z and E_{fs} are relevant constants. Other side constraints can also be modelled the same way as private constraints. The next section presents a Generalised Optimal Loading Model which includes all those types of constraints.

7.5 Generalized Optimal Loading Model

The generalized OLM uses the indices, parameters, and variables (other than the individual response coefficients) used in the basic OLM. The additional indices, parameters, and variables are defined below.

Indices:

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[31] The separation of receptor constraints is more important in extending the trading systems to include point sources. Chapter 11 discusses how to include point sources.

n = node (location): 1,…, N.

i = source constraint: 1, …, I.

j = multi-receptor/period constraint: 1, 2,…, J.

g = private or side constraint: 1, …, G.

Parameters:

H_{nrd} = increase in nitrate level that occurs at receptor r, d years after unit (1 kg) nitrate loading in node n during a single year (kg or mg/l).

V_i = loading limit specified by source constraint i (kg).

W_j = the right-hand-side constant for multi-receptor/period constraint j (kg or mg/l). W_j is a restriction on one or many receptors over one or may time periods.

Z_g = the right-hand-side constant for private or side constraint g (kg). Z_g can be either a private restriction or an externally imposed restriction on permit allocations.

A_{nsi}, B_{rtj}, and E_{fsg} are unitless constraint coefficients (possibly zero or one).

Decision variables:

q^{nodal}_{ns} = nitrate loading from node n in year s. This is the total year-s loading permit allocation to the farms in node n (kg).

y_{rt} = total allocation of receptor capacity (capacity of receptor r of year t) (kg or mg/l).

Model: Generalized OLM

Maximize $\sum_f \sum_s \sum_k P_{fsk} x_{fsk}$, subject to:

Upper and lower bounds on bid tranches

$x_{fsk} \le U_{fsk}$ for all f, s, and k. (P-1) θ^{+}_{fsk}

$-x_{fsk} \le 0$ for all f, s, and k. (P-2) θ^{-}_{fsk}

Calculation of individual and nodal allocations

$\sum_k x_{fsk} - q_{fs} = 0$ for all f and s. (P-3) μ_{fs}

$\sum_{f \in n} q_{fs} - q^{nodal}_{ns} = 0$ for all n and s. (P-5) β_{ns}

Loading constraints

$\sum_f\sum_s A_{nsi}q^{nodal}{}_{ns} \le V_i$ for all i. (P-6) π_i

Private and side constraints

$\sum_f\sum_s E_{fsg}q_{fs} \le Z_g$ for all g. (P-7) σ_g

Calculation of receptor capacity allocations

$\sum_f \sum_{s=\max(1,t-T)}^{\min(t,S)} H_{nr(t-s)}q^{nodal}{}_{ns} - y_{rt} = 0$ for all r and t. (P-8) γ_{rt}

Receptor capacity constraints

$y_{rt} \le C_{rt}$ for all r and t. (P-9) λ_{rt}

Multi-receptor/period constraints

$\sum_r\sum_t B_{rtj}y_{rt} \le W_j$ for all j. (P-10) δ_j

Since each additional constraint has an associated shadow price, the constraint structure, and hence the price structure of the generalized OLM, is more complicated than that of the basic OLM.

7.5.1 Dual Formulation and Shadow Prices

The dual of the generalized OLM models the problem of valuating the receptor capacities and all the other receptor and source based restrictions imposed on the permit market.

Minimise $\sum_f\sum_s\sum_k U_{fsk}\theta^+{}_{fsk} + \sum_i V_i\pi_i + \sum_g Z_g\sigma_g + \sum_r\sum_t C_{rt}\lambda_{rt} + \sum_j W_j\delta_j$, subject to:

$\theta^+{}_{fsk} - \theta^-{}_{fsk} + \mu_{fs} = P_{fsk}$ for all f, s, and k. (D-1) x_{fsk}

$-\mu_{fs} + \beta_{ns} + \sum_g E_{fsg}\sigma_g = 0$ for all f and s. (D-3) q_{fs}

$-\beta_{ns} + \sum_i A_{nsi}\pi_i + \sum_r \sum_{t=s}^{s+D} H_{nr(t-s)}\gamma_{rt} = 0$ for all n and s. (D-5) $q^{nodal}{}_{ns}$

$-\gamma_{rt} + \lambda_{rt} + \sum_j B_{rtj}\delta_j = 0$ for all r and t. (D-6) y_{rt}

$\theta^+{}_{fsk}$ and $\theta^-{}_{fsk} \ge 0$ for all f, s, and k.

μ_{fs} free for all f and s.

β_{ns} free for all n and s.

$\sigma_g \geq 0$ for g.

$\pi_i \geq 0$ for i.

γ_{rt} free for all r and t.

$\lambda_{rt} \geq 0$ for all r and t.

$\delta_j \geq 0$ for all j.

The shadow price β_{ns} of the constraint (P-5) which defines $q^{nodal}{}_{ns}$, for some n and s, indicates how much the objective function would increase if another 1 kg of year-s loading permits were given to node n; this is the social marginal cost of nitrate loading from node n in year s. We call β_{ns} the "nodal loading price". Unlike the participant price, the nodal loading price is a locational price which is not indexed to a particular participant, and it does not vary among individual farms in the same node based on any private constraint (or other side constraint) which applies to q_{fs}. Since the nodal loading price is a market price determined by the nodal demand and supply, it can be directly charged to each farm in node n.

The shadow price π_i associated with a source constraint i (P-6) indicates the marginal economic contribution of a unit relaxation (increase) in the associated loading limit V_i. The farms in the affected nodes would pay a price of π_i for relaxing the limit by 1 kg. For example, if V_i is a regional loading limit, π_i is the price that the farms in the region would pay per unit increase of the limit. The ability of a groundwater aquifer to accept nitrates and thus the regional loading limits may be increased by nitrate reduction or remediation methods such as building wetlands and laying permeable reactive barriers (Kalmar & Byrnes, 2008). Importantly, the price π_i signals the value of investment in those remediation and reduction projects.

The shadow price σ_g of a private constraint (P-7) specified by farm f indicates the additional profit that the farm could have gained if the relevant restriction was relaxed by 1 kg. For example, if a farm submitted a condition requiring the same quantity in the next two years, then the shadow price of the associated constraint indicates how much additional profit the farm would gain if it allows a difference of up to 1 kg between the final permit positions for the next two years, rather than requiring exactly the same quantity. Hence, this is the opportunity cost of a private restriction.

On the other hand, if g is a side constraint which affects one or many farms, then the associated shadow price σ_g indicates how much the objective function would increase if the restriction was relaxed (increased) by 1 kg. In this case, the price σ_g provides feed-back information to the authorities who have imposed the restrictions, indicating the cost incurred by the restriction.

The dual variable γ_{rt} associated with the primal constraint (P-8) which defines y_{rt} indicates that the farms would make an incremental profit of γ_{rt} if they were allowed to increase the nitrate level at receptor r in year t by another one unit. Thus, they should be charged at γ_{rt} per unit increase in nitrate level at receptor r in year t (based on the marginal cost pricing approach).

Once more, the shadow price λ_{rt} of the receptor capacity constraint (P-9), for some r and t, describes the marginal value of the nitrate intake capacity of receptor r in year t and hence the *market price* of the receptor capacity.

Since W_j is a restriction that affects one or many receptors over one or many time periods, the shadow price δ_j of a multi-receptor/period constraint j (P-10) indicates the marginal value of a unit increase in the relevant receptor-end restriction. The farms would pay δ_i per unit relaxation (increase) of the limit on cumulative capacity allocation.

7.5.2 Price Structures and Relationships

As discussed above, λ_{rt} is the market equilibrium price of receptor capacity, and γ_{rt} is the *farm* price for receptor capacity, the marginal cost based price that should be charged from (or paid to) the farms for receptor capacity. However, the capacity owners who lease out receptor capacities (the regulator, if the farms have not previously bought the total capacity of receptor r in year t)[32] should be paid at rate λ_{rt} for each unit of receptor capacity sold (leased out).

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[32] Note that we have assumed no permanent or long term nitrate loading rights held by the farms.

The dual constraint (D-6) associated with primal variable y_{rt} describes the relationship between γ_{rt} and λ_{rt} as $\gamma_{rt} = \lambda_{rt} + \sum_i B_{rti}\delta_i$. This relationship shows that the receptor capacity price charged to the farms, for some receptor *r* and period *t*, is determined by the associated capacity constraint and other receptor end constraints affected by receptor *r* in period *t*. If none is binding, the receptor price charged to the farms can be zero.

As mentioned earlier, multi-receptor/period constraints (indexed by *j*) possibly correspond to nitrate residence and transport in surface water. Hence, for groundwater receptors, and for unconnected surface water receptors with nitrate residence times of less than a year, the farms will have to pay only the cleared capacity price, i.e, $\gamma_{rt} = \lambda_{rt}$. But if a surface water receptor *r* is an upstream water body from which water flows down to another receptor, and/or if nitrate residence time in the receptor is considerably longer than a year, then the farms will have to pay the cleared capacity price plus a price for each other affected receptor-end constraint.

If the nitrate level at receptor *r* in year *t* has critical impacts on the many multi-receptor/period constraints, farms may have to pay a higher price for receptor capacity, even if the associated capacity constraint itself is non-binding. For example, relatively clean sub-catchments performing well below the maximum acceptable nitrate discharge into local streams or lakes may still incur non-zero prices, because major downstream rivers or lakes are at a critical state, with binding environmental constraints. This is a proper reflection of the impact that their discharges will eventually have on those downstream receptors. Conversely, relatively polluted sub-catchments will have to pay a higher price, reflecting local pollution impacts, even though downstream rivers or lakes may not be in a critical state.

The dual constraint (D-5) associated with primal variable q^{nodal}_{ns} describes the components of the nodal prices which are used to clear the market. The nodal price is composed of the receptor capacity prices charged (or paid) to the farms, and the prices associated with other source based (market) constraints.

$$\beta_{ns} = \sum_r \sum_{t=s}^{s+T} H_{zr(t-s)}\gamma_{rt} + \sum_i A_{nsi}\pi_i$$

If no source constraints were present, or if all were non-binding ($\pi_i = 0$), the nodal loading price equals the value of the bundle of receptor permits equivalent to a unit (1 kg) loading permit allocated to node n, i.e., $\beta_{ns} = \sum_r \sum_{t=s}^{s+T} H_{zr(t-s)} \gamma_{rt}$. If a source constraint binds the solution, then the farms in the affected node(s) will have to pay the price of an equivalent receptor permit bundle plus the price associated with the binding source constraint. Hence the nodal prices include the market values attached to the restrictions on locational nitrate loading.

The dual constraint (D-4) associated with primal variable q_{fs} describes the relationship between the nodal prices and the participant prices as $\mu_{fs} = \beta_{ns} + \sum_g E_{fsg}\sigma_g$. In the absence of any binding private or side constraint, each farm's participant price would equal the nodal price. In this case, the market allocation is in strict merit order, because the price actually charged and paid to the farm is equal to the participant price which rations the final permit allocation.

However, if a binding private constraint or a side constraint stops a farm from buying more until his or her marginal profit equals the nodal price β_{ns}, the participant price (the farm's marginal value of the next 1 kg) is still above the nodal price. In this case, the nodal price alone would not justify the final allocation, in terms of the bid prices. But the nodal price, in combination with the shadow price(s) on binding private and side constraint(s), forms a participant price that at which the final allocation is optimal, in terms of the bid prices.

In summary, the market values of nitrate loading permits are driven by three main factors: (1) receptor capacity constraints, (2) multi-receptor/period constraints, and (3) source constraints. The prices associated with these constraints (λ_{rt}, π_i, and δ_j) ultimately determine how much each farm has to pay or will receive for loading permits. These prices can be considered as commodity prices, whereas γ_{rt} and β_{ns} are locational prices derived from the commodity prices.

However, only a few of the above constraints will tend to bind the generalized OLM solution. If the farms in some node do not affect any of the binding constraints, the nodal price will be zero, allowing the farms to buy all they bid at price zero.

7.6 Settlement and Surpluses

As discussed above, the nodal prices are determined by all the market constraints (receptor capacity constraints, multi-receptor/period constraints, and source constraints). The settlement process will be simpler if only capacity constraints were present or if the other market constraints were non-binding. Therefore, we first discuss the settlement issues ignoring all market constraints other than capacity constraints. In this case, the initial distribution of permits is the main factor which determines the revenue distribution.

Regardless of whether the farms possess any permanent or long term loading rights, they may possess previously purchased loading permits (leased-in previously from the market), because the trading program allows them to trade permits for S years from the upcoming year. Let Q^*_{fs} be the initial (pre-trade) year-s permit position of farm f in kg.

If $q_{fs} > Q^*_{fs}$, then farm f is a net buyer of year-s loading permits. The payment due from farm f in node n for buying year-s loading permits is $\beta_{ns} \times (q_{fs} - Q^*_{fs})$. If $q_{fs} < Q^*_{fs}$, then f is a net seller of year-s loading permits. The payment due to farm f in node n for selling year-s permits is $\beta_{ns} \times (Q^*_{fs} - q_{fs})$. If $q_{fs} = Q^*_{fs}$, farm f is neither buying nor selling year-s loading permits.

Let Ω be the net revenue for the market operator after clearing the payments for all the *farms* for all the S years (after collecting money from all the buyers and paying all the sellers).

$$\Omega = \sum_n \sum_s \beta_{ns} \times \sum_{f \in n} (q_{fs} - Q^*_{fs}).$$

Theorem 1: if the initial distribution of loading permits is feasible (i.e., if the initial distribution of permits meet all the market constraints in the market clearing LP), then operator revenue Ω is non-negative.

Theorem 2: if the initial distribution of loading permits fully allocates all the receptor capacities (i.e., if the initial allocation binds all the capacity constraints), then Ω is zero.

Theorem 3: if the initial distribution of loading permits is infeasible, then **Ω** can be negative.

From complementary slackness,

$$\left(\sum_n \sum_{s=\max(1,t-D)}^{\min(t,S)} H_{nr(t-s)} q^{nodal}{}_{ns} - C_{rt}\right)\lambda_{rt} = 0 \text{ for all } r \text{ and } t. \quad \text{(S1)}$$

Since $q^{nodal}{}_{ns} = \sum_{f\in n} q_{fs}$,

$$\left(\sum_n \sum_{s=\max(1,t-D)}^{\min(t,S)} H_{nr(t-s)} \sum_{f\in n} q_{fs} - C_{rt}\right)\lambda_{rt} = 0 \text{ for all } r \text{ and } t. \quad \text{(S2)}$$

If the initial distribution of loading permits is feasible, then

$$\sum_n \sum_{s=\max(1,t-D)}^{\min(t,S)} H_{nr(t-s)} \sum_{f\in n} Q^*{}_{fs} \le C_{rt} \text{ for all } r \text{ and } t. \quad \text{(S3)}$$

Since $\lambda_{rt} \ge 0$, $\left(\sum_n \sum_{s=\max(1,t-D)}^{\min(t,S)} H_{nr(t-s)} \sum_{f\in n} Q^*{}_{fs} - C_{rt}\right)\lambda_{rt} \le 0$ for all r and t. (S4)

From (S2) − (S4), $\left(\sum_n \sum_{s=\max(1,t-D)}^{\min(t,S)} H_{nr(t-s)} \sum_{f\in n} (q_{fs} - Q^*{}_{fs})\right)\lambda_{rt} \ge 0$ for all r and t.

Hence, $\sum_r \sum_{t=1}^{S+D} \left(\sum_n \sum_{s=\max(1,t-D)}^{\min(t,S)} H_{nr(t-s)} \sum_{f\in n} (q_{fs} - Q^*{}_{fs})\right)\lambda_{rt} \ge 0$, and

$$\sum_n \sum_r \sum_{t=1}^{S+D} \left(\sum_{s=\max(1,t-D)}^{\min(t,S)} H_{nr(t-s)} \sum_{f\in n} (q_{fs} - Q^*{}_{fs})\right)\lambda_{rt} \ge 0 .$$

Define $\sum_{f\in n} (q_{fs} - Q^*{}_{fs}) = q^{net}{}_{ns}$ and $\sum_{s=\max(1,t-D)}^{\min(t,S)} H_{nr(t-s)} q^{net}{}_{ns} = fun(n,r,t)$. (S5)

$$\text{Then } \sum_n \sum_r \sum_{t=1}^{S+D} fun(n,r,t)\lambda_{rt} \ge 0 . \quad \text{(S6)}$$

The terms $fun(n,r,t)\lambda_{rt}$ for t = 1 to S+D can be written as follows.

$fun(n,r,1)\lambda_{r1} = (H_{nr0}q^{net}{}_{n1})\lambda_{r1}$

$fun(n,r,2)\lambda_{r2} = (H_{nr0}q^{net}{}_{n2} + H_{nr1}q^{net}{}_{n1})\lambda_{r2}$

$fun(n,r,3)\lambda_{r3} = (H_{nr0}q^{net}{}_{n3} + H_{nr1}q^{net}{}_{n2} + H_{nr2}q^{net}{}_{n1})\lambda_{r3}$

....

$fun(n,r,S)\lambda_{rS} = (H_{nr0}q^{net}{}_{nS} + H_{nr1}q^{net}{}_{n(S-1)} + H_{nr2}q^{net}{}_{n(S-2)} \ldots + H_{nr(S-1)}q^{net}{}_{n1})\lambda_{r3}$

$fun(n,r,S+1)\lambda_{r(S+1)} = (H_{nr1}q^{net}{}_{nS} + H_{nr2}q^{net}{}_{n(S-1)} + H_{nr3}q^{net}{}_{n(S-2)} \ldots + H_{nrS}q^{net}{}_{n1})\lambda_{r(S+1)}$

$$fun(n,r,S+2)\lambda_{r(S+2)} = (H_{nr2}q^{net}{}_{nS} + H_{nr3}q^{net}{}_{n(S-1)} + H_{nr4}q^{net}{}_{n(S-2)} \dots \quad + H_{nr(S+1)}q^{net}{}_{n1})\lambda_{r(S+2)}$$

....

$$fun(n,r,S+D-1)\lambda_{r(S+D-1)} = (H_{nr(D-1)}q^{net}{}_{nS} + H_{nrD}q^{net}{}_{n(S-1)})\lambda_{r(S+D-1)}$$

$$fun(n,r,S+D)\lambda_{r(S+D)} \qquad = H_{nrD}q^{net}{}_{nS}\lambda_{r(S+D)}$$

By summing the above terms: $fun(n,r,1)\lambda_{r1}$ to $fun(n,r,S+D)\lambda_{r(S+D)}$,

$$\sum_{t=1}^{S+D} fun(n,r,t)\lambda_{rt} = \sum_{s}\sum_{t=s}^{s+D} H_{nr(t-s)}q^{net}{}_{ns}\lambda_{rt}$$

By substituting in (S6),

$$\sum_{n}\sum_{r}\sum_{s}\sum_{t=s}^{s+D} H_{nr(t-s)}q^{net}{}_{ns}\lambda_{rt} \geq 0 .$$

$$\sum_{n}\sum_{s}\sum_{r}\sum_{t=s}^{s+D} H_{nr(t-s)}\lambda_{rt}q^{net}{}_{ns} \geq 0 .$$

By substituting $q^{net}{}_{ns} = \sum_{f\in n}(q_{fs} - Q^*{}_{fs})$,

$$\sum_{n}\sum_{s}\sum_{r}\sum_{t=s}^{s+D} H_{nr(t-s)}\lambda_{rt}\sum_{f\in n}(q_{fs} - Q^*{}_{fs}) \geq 0 .$$

$$\sum_{n}\sum_{s}\left(\sum_{r}\sum_{t=s}^{s+D} H_{nr(t-s)}\lambda_{rt}\right)\left(\sum_{f\in n}(q_{fs} - Q^*{}_{fs})\right) \geq 0 .$$

Since $\sum_{r}\sum_{t=s}^{s+D} H_{nr(t-s)}\lambda_{rt} = \beta_{ns}$, then

$\sum_{n}\sum_{s}\beta_{ns} \times \sum_{f\in n}(q_{fs} - Q^*{}_{fs}) \geq 0$, and hence Ω is non-negative (Theorem 1).

If the initial allocation binds all the capacity constraints, inequalities S3 and S4 become equalities. Then, $\sum_{n}\sum_{s}\beta_{ns} \times \sum_{f\in n}(q_{fs} - Q^*{}_{fs}) = 0$, and hence Ω is zero (Theorem 2). Further, if either $\lambda_{rt} = 0$ or $\sum_{f}\sum_{s=\max(1,t-D)}^{\min(t,S)} H_{fr(t-s)}Q^*{}_{fs} - C_{rt} = 0$ then,

$\left(\sum_{f}\sum_{s=\max(1,t-D)}^{\min(t,S)} H_{fr(t-s)}Q^*{}_{fs} - C_{rt}\right)\lambda_{rt} = 0$ for all r and t.

Hence, all the ex-post binding constraints being bound by the initial allocation is a sufficient condition for **Ω** = 0.

Similarly, if the initial distribution of permits is infeasible, inequalities (S3) and (S4) do not hold for some r and t, and hence Ω can be negative (Theorem 3).

Since we assume no permanent permit holdings, only the permits previously purchased from the trading program are considered as initial holdings. A previous market allocation cannot cause infeasibility unless the previous capacity estimates were inaccurate or some unexpected event occurred (e.g., a flood). Therefore, the operator revenue Ω cannot be negative.

7.6.1 Interpretation of Operator Revenue

As proved above, if the initial distribution of permits is feasible, Ω is non-negative, but what does a positive operator revenue mean? We defined Ω as the operator revenue after clearing the payments for the *farms*, but the receptor capacities bought from the farms could have been sold by either the farms (who bought previously) or by the regulator who is assumed to be the owner of the receptor capacities. If the farms do not possess any previously purchased permits, Ω is the total payment made by the farms for buying (or leasing in) receptor capacity rights from the regulator. Then, Ω is the total lease payment due to the regulator. If the farms currently possess loading permits, and if the initial distribution of loading permits binds all the capacity constraints (or at least the ex-post binding capacity constraints), Ω is zero. The market re-allocation being bound by a capacity constraint which was not binding the initial allocation means that the farms have bought receptor capacity from the regulator up to the maximum available, and that Ω is non-zero. If the initial allocation was infeasible, Ω may be negative, as the regulator has to buy back the over-allocated receptor capacities. Such payments will tend to offset one another if the capacities of some receptors and/or years were previously over-allocated, and some under-allocated.

The regulator can collect the lease payments as a public property owner, or can re-distribute the total revenue or a portion of the revenue among the market participants, based on some free initial allocation criteria. In the latter case, all the farms will be deemed to have an initial permit position (in addition to previous purchases). However, it is difficult to find a fair initial allocation of loading permits which binds all the ex-post binding capacity constraints. Therefore, if the regulator wants to redistribute the total revenue among the farms (to set $\Omega = 0$), the free initial allocation can be made in terms of receptor capacity rights rather than loading permits. In Chapter 10 there is more discussion on setting the initial positions.

7.6.2 Settlement Surpluses

The operator revenue Ω discussed above is not a settlement surplus resulting from price differences; it is just a rental payment due to someone who owns the receptor capacity. Hence if the receptor capacities were the only physical limitation, the market is free from any surplus issues. This section considers a market which has all types of physical constraints: capacity constraints, multi-receptor/period constraints, and source constraints. We define a settlement surplus as a surplus left after settling the payments for the farms and the owners of receptor capacity.

In the presence of multi-receptor/period constraints and source constraints, the nodal prices are calculated as $\beta_{ns} = \sum_r \sum_{t=s}^{s+T} H_{nr(t-s)}\gamma_{rt} + \sum_i A_{nsi}\pi_i$. The price charged to the farms for receptor capacity γ_{rt} is given as $\gamma_{rt} = \lambda_{rt} + \sum_i B_{rti}\delta_i$. When the buyers (farms) are charged at γ_{rt} and the capacity owners (other than farms) are paid at λ_{rt}, the market would clear with surplus revenue, because the same final commodity is traded at different prices. The surplus is explained by the amount paid by the farms for the binding multi-receptor/period constraints. Similarly, when the farms which affect a binding source constraint are charged at a rate which includes the price associated with that constraint, and the others are paid at a price which does not include the price associated with that constraint, the market will clear with surplus revenue.

To handle the settlement surpluses related to the binding multi-receptor/period and source constraints, the market regulations require a precise interpretation of each market constraint. The farms cannot utilize the receptor capacities beyond the limits specified by other market constraints such as regional loading limits. Hence, the rights to affect multi-receptor/period constraints and source constraints can be considered as essential *environmental services* required to utilize the core commodity (receptor capacity) traded[33]. The prices associated with those constraints, π_i and δ_j, are the market values of those environmental services. When they are included in the nodal prices, they generate settlement surpluses[34]. The question is: who should collect the money paid for those constraints? The market requires a mechanism for handling the possible surpluses. The problem of handling the surpluses generated by those constraints is similar to the problem of handling the rental surpluses associated with transmission line capacity constraints in electricity markets. The issues and alternatives are discussed in Hogan (1992), Oren et al. (1995), and Read (2002).

One way to handle surplus payments is to avoid any surplus by defining tradable rights for each market constraint (including capacity constraints) and let them be traded separately in a combined market, so that the farms can simultaneously trade receptor capacities and other environmental services[35]. To understand this, we use a general representation of the market constraints.

As discussed in section 7.4, all source and receptor based (market) constraints may be generally modelled as $\sum_f \sum_s A_{ns\tilde{\imath}} q^{nodal}{}_{ns} \leq V_{\tilde{\imath}}$, where $\tilde{\imath} = 1, \ldots, \tilde{I}$ is an index for the market constraint, and $A_{ns\tilde{\imath}}$ and $V_{\tilde{\imath}}$ are some constants.

We may define "constraint rights" as tradable rights to affect each constraint $\tilde{\imath}$, and expect the farms to assemble a portfolio of constraint rights to match the nitrate loading in each year. A constraint right may correspond to a right for receptor capacity or an environmental service, and $V_{\tilde{\imath}}$ is the tradable capacity of the constraint right (constraint capacity). This is the same as the ambient or receptor permit system discussed in Chapters 4 and 5, which is not practically applicable for trading nitrate,

[33] Similarly, electricity users in a node cannot use electricity beyond the physical limits of the incoming transmission system. Hence the transmission system is an essential service required to utilize the core product, electric power.

[34] Similar to the rental surpluses associated with transmission line capacity constraints in electricity markets.

[35] Defining tradable rights relative to some constraints such as multi-period constraints may cause confusion. Trading rights to pollute a receptor in each year, together with rights to pollute a receptor any time within a period of several consecutive years, are confusing.

because the number of constraints involved is relatively large. However, if only a few market constraints other than receptor capacity constraints are present (for example, one source constraint on total nitrate loading with a hundred receptor capacity constraints), the farms may be allowed to trade loading permits (bundles of capacity constraint rights) and separate constraint rights for other market constraints, in a combined market.

Rather than trading rights defined relative to any constraint separately, the market could allow the farms to trade fully packaged products, bundles of constraint rights for receptor capacities and other environmental services. This is easier for the farms, because the loading permits are already defined as bundles of receptor capacity rights, and they can be re-defined as bundles of not only receptor capacity rights but all the (market) constraint rights. This is reasonable, because each market constraint specifies the ability of some water body (or a portion of a water body) to accept nitrate.

Under any of the above options, the total revenue from sales will be distributed among the market participants (the farms which sell permits) and the owners of constraint rights who do not participate in the market. If the constraint rights are not fully distributed among the farms ex-ante, the regulator can be considered as a property owner who leases out the rights to use them.

Another way to handle surplus payments associated with a market constraint is to treat the constraint as a restriction on the capacity of an environmental service provided to the market by someone outside the market; the service is not traded among the market participants, and the facility owner does not participate in the market. Then the surplus revenue associated with the constraint should be paid to the external capacity owner[36]. For example, the surpluses may be paid to the regional environmental authority as a payment for undertaking remediation projects to clean the threatened water bodies.

[36] This is similar to the concept of paying the surpluses generated from binding transmission line capacity constraints in electricity markets to the transmission network operator.

Another option is re-distributing the surplus among the market participants based on some criteria, for example, in proportion to the final permit positions.

7.7 Gains from Trade

An interesting question is how much benefit each farm gains from participating in the trading program. As shown in Figure 7.3, if the initial position is to the left of q_{fs}, f is a net buyer of year-s permits, and if the initial position is to the right of q_{fs}, f is a net seller of year-s permits (the unaccepted gross poll bids of the net sellers are equivalent to accepted net pool offers). The graph highlights the buyer and seller surpluses relative to the participant prices; in the absence of any binding private or side constraint the nodal price and the participant price are equal.

Generally, if $P(q)$ is the profit function, buyer and seller surpluses can be given by $\int_{Q^*_{fs}}^{q_{fs}} P(q).dq - \mu_{fs} q_{fs}$ and $\int_{Q^*_{fs}}^{q_{fs}} \mu_{fs} q_{fs} - P(q).dq$. If the nodal price differs from the participant prices, the nodal price β_{fs} should be used to calculate the surpluses. As shown in the figure, buyer and seller surpluses can also be calculated using the shadow prices associated with the upper and lower bounds on the bids. For example, if the initial position of farm f was zero, f is a net buyer of year-s permits, and the buyer surplus is $\sum_k \sum x_{fsk}\, \theta^+_{fsk}$. If the initial position of farm f was $\sum_k U_{fsk}$, f is a net seller of year-s permits, and the seller surplus is $\sum_k \sum x_{fsk}\, \theta^-_{fsk}$.

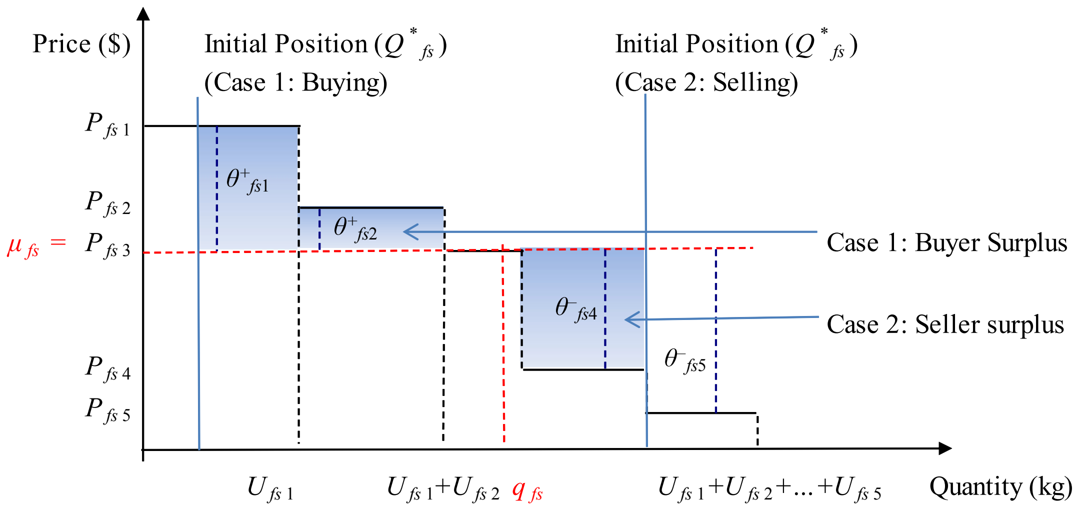

Figure 7.3: Buyer and seller surpluses. Depending on the initial position, a farm can be either a buyer or a seller of some year-*s* permits, but cannot be buying and selling the same year-*s* permits; hence the two cases are just two possible initial positions.

7.8 Limitations of the OLM

The proposed market model allows only farms to participate in the market and trade loading permits. Unless the farms possess previously purchased permits and offers to sell, the proposed trading program is a single-sided, buyer's market. The prices are determined solely by competition among the farms. The regulator who owns the previously unsold receptor capacities does not actively participate in the market. Regulator owned capacity may be sold for price zero, because the regulator is assumed to have a continuous reserve of price zero.

The market allocates the future nitrate intake capacities of the water bodies for current consumption of the farms. As a consequence, future opportunities for nitrate loading (farming) could be forgone. The opportunity cost of being unable to discharge nitrates in the future is not represented in the models. On the other hand, the ecological cost and the water user's cost of having nitrate in water are also disregarded. The regulator, who is assumed to be the owner of the environment on behalf of the public interest, could possibly have imposed those costs on the polluters.

The proposed LP calculates the optimal prices and allocations based on the tradable receptor capacities C_{rt}. The tradable capacity (capacity released to the market) is a management decision based on the currently available capacity C^0_{rt} (how much more nitrate each receptor can take in each time period). Since, the available capacity of some year t may be allocated in any year before year t, subject to the demand, the tradable capacity (capacity released to the market in this year) may be set below the available capacity ($C_{rt} \leq C^0_{rt}$) to reserve some of the capacity for future allocation.

If the total available capacity was released to the market right away, i.e., if $C_{rt} = C^0_{rt}$ (all-in-market), the participants collectively decide whether they consume the total capacity now, or leave some for the future. Then, whether or not the receptor capacities are fully allocated currently (ex-ante), any capacity constraint may be fully allocated by the market (ex-post). If a capacity constraint for some year t becomes binding in the solution, the capacity of year t is fully consumed by year 1 to year S permits traded in the current auction. As a consequence, farms may not be able to buy any permit that affects year t in the future, unless someone who had bought a future permit which affects year t, offers to sell, or the capacity can be augmented.

Another disadvantage of fully allocating the resource capacities immediately is that the available capacity $C^0{}_{rt}$ is an estimate that may not be accurate. If the actual capacity availability is below the estimate, the environmental goals will not be achieved. Therefore, it is always risky to fully allocate the estimated capacity to be consumed immediately in a few years. Then, the market authorities are left with a potentially difficult optimisation problem: how much capacity should be released to the market each time trading takes place? This is a problem of balancing resource consumption over time. In the next chapter, we discuss alternative mechanisms to solve the problem.

Chapter 8

8 Trade in Loading Permits and Capacity Rights[37]

8.1 Introduction

The major problem in the generalized OLM is the risk of premature consumption of future capacities. A trivial method to avoid premature capacity consumption and to balance resource consumption over a long planning horizon is releasing only a portion of the currently available receptor capacity into the market and reserving some for the future. However, the market authorities have to decide how much should be released to the market each time. Another method is to set a penalty on each unit of resource consumed beyond some limit. Again, the authorities have to choose the penalty margin and the rate. Those control-based methods require the environmental authorities to decide the total allocations or penalties based on forecasted demands. Such mechanisms push the market further away from free trading. A potentially better method is to facilitate the market itself to collectively decide when and how much to consume.

The proposed market model had only farms trading loading permits and no one trading receptor capacity rights (directly), or more generally speaking, no one trading

[37] This chapter is based on Prabodanie et al. (2010).

constraint rights (directly). As discussed in the previous chapter, the regulator plays a passive role, leaving the farms to determine the lease prices, and hence the true social cost of allocating capacity is not represented in the model. If the regulator could participate in the market and sell receptor capacity rights, it can impose the associated costs on the market, and balance allocations over time.

Apart from the regulator, if other entities such as environmental organizations and farm organizations could participate in the market and trade receptor capacity rights, they can buy future capacity from the market (by competing with the farms) and save for the future, or retire for the enhancement of environmental quality. Such entities can help the balancing of capacity utilization over time. Therefore, the market should be expanded to allow trade in capacity rights, or more generally, to allow trade in "constraint rights," together with loading permits and to encourage participation of third parties to balance pollution (capacity consumption) over time and to avoid over-consumption of capacity by low value uses.

8.2 Trading Loading Permits and Constraint Rights

In this chapter, we present a market model with two types of players, farms trading loading permits, and "resource banks" trading constraint rights in the same combined market. Ideally, anyone, including the farms, should be able to trade constraint rights. However, to avoid confusion, we assume that the farms trade only loading permits because the constraint rights purchased from the market cannot be directly utilized (surrendered to cover nitrate loading). Those who buy constraint permits can only re-sell to recover costs and make profits, or retire the permit for the sake of the environment. A farm wanting to trade both loading permits and constraint rights is considered to be participating in the market as two independent players: a farm and a bank. The market itself is indifferent to any vertical integration or bilateral contract agreed outside the market[38].

[38] This is an essential feature of a gross pool formulation. In electricity markets, regardless of the fact that a generator and a retailer are vertically integrated, or have a bilateral trading contract (for example, to hedge against the market price volatility, a retailer may agree with a generator to buy power at an agreed price),

A catchment scale market would be likely to have just one bank, the regional environmental authority or a representative organization (the regulator). The regulator who owns the currently unallocated resource capacities would offer to sell constraint rights and the farms would bid to buy (as bids for loading permits). The market participation of the regulator creates a market place in which each unit of receptor capacity and environmental service in the market has an owner who sets a value on the commodity.

The regulator may set a single reservation price on each type of constraint right, or a stepped offer function. The market operator can transform the offer function to an equivalent stepped bid function. If the capacity of a market constraint is fully or partially owned by the regulator, it can set the prices for each offer tranche based on the associated costs (which are hard to estimate, as discussed in Chapter 9), or some planned allocation schedule. For example, if the total available capacity is 500 kg, and if the regulator wishes to allocate only about 100 kg to the farms in the current trading year, it may set a relatively low price on the first 100 kg tranche. If the regulator wishes to reserve some of the capacity for the future, it can set a high price on the last offer tranche, for example, an infinitely high price on the last 200 kg tranche offered.

8.3 Optimal Resource Allocation Model (ORAM)

We present a model to facilitate any number of banks participating in the market. The banks bid for each constraint separately and farms bid for loading permits equivalent to bundles of constraint rights. The banks also have to bid for steps of quantities starting from zero (offers can be converted to gross pool bids as discussed in Chapter 6). Since the market clearing LP itself does not discount the bids, the bids for future

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the market treats them as two independent traders having independent marginal cost or profit functions. Once the market is cleared, everyone should make payments based on cleared prices. Outside the market, the contracts are exercised based on the differences between the contract prices and the market prices.

capacities should indicate the discounted present value of the future capacities, based on each bank's own private discount rate[39].

For this model, we assume that tradable constraint rights are defined for each market constraint, and the farms trade fully packaged loading permits (bundles of constraint rights) while banks trade constraint rights separately. We use a common index for all market constraints including the receptor capacity constraints and provide a compact, general LP model which can be used to clear a market in which the farms and the banks trade loading permits and constraint rights simultaneously. A set of new indices, parameters, and variables are used in model ORAM with those which were defined before.

Indices:

b = bank: 1,…, B.

l = bank bid tranche: 1,…, L.

$\tilde{\imath}$ = market constraint: 1, …, $\tilde{I}$ ($\tilde{I} = R \times \mathrm{T} + I + J$). Since each constraint $\tilde{\imath}$ corresponds to a commodity traded in the market, in this section, we use the word "constraint" rather than the term "constraint right," to refer to a commodity.

Parameters:

$U^{Bank}{}_{b\tilde{\imath}l}$ = quantity specified in bid tranche l submitted by bank b for constraint $\tilde{\imath}$ (kg or mg/l).

$P^{Bank}{}_{b\tilde{\imath}l}$= bid price specified in bid tranche l submitted by bank b for constraint $\tilde{\imath}$ ($/kg or $/mg/l).

$C_{\tilde{\imath}}$ = tradable capacity of constraint $\tilde{\imath}$ (kg or mg/l).

$\tilde{A}_{\tilde{\imath}ns}$= constraint coefficient associated with node n and year s.

Decision variables:

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[39] The regulator who participates in the market as a resource bank will have to bid for capacity rights based on the discounted present values over a long planning horizon. In chapter 9, we discuss the major issues arise in valuating future capacity.

$x^{bank}_{b\tilde{\imath}l}$ = quantity accepted from bid tranche l submitted by bank b for constraint $\tilde{\imath}$ (kg or mg/l).

$q^{bank}_{b\tilde{\imath}}$ = aggregate final position of constraint $\tilde{\imath}$ for bank b; this is the capacity of constraint $\tilde{\imath}$ held by bank b after trade (kg or mg/l).

Model: ORAM

Maximize $\sum_f \sum_s \sum_k P_{fsk} x_{fsk}, + \sum_b \sum_{\tilde{\imath}} \sum_l P^{Bank}_{b\tilde{\imath}l} x^{bank}_{b\tilde{\imath}l}$, subject to:

Upper and lower bounds on bid tranches

$x_{fsk} \le U_{fsk}$ for all f, s, and k. (P-1) θ^{+}_{fsk}

$-x_{fsk} \le 0$ for all f, s, and k. (P-2) θ^{-}_{fsk}

$x^{bank}_{b\tilde{\imath}l} \le U^{Bank}_{b\tilde{\imath}l}$ for all b, $\tilde{\imath}$, and l. (P-11) $\alpha^{+}_{b\tilde{\imath}l}$

$- x^{bank}_{b\tilde{\imath}l} \le 0$ for all b, $\tilde{\imath}$, and l. (P-12) $\alpha^{-}_{b\tilde{\imath}l}$

Calculation of final permit positions

$\sum_k x_{fsk} - q_{fs} = 0$ for all f and s (P-3) μ_{fs}

$\sum_l x^{bank}_{b\tilde{\imath}l} - q^{bank}_{b\tilde{\imath}} = 0$ for all b and $\tilde{\imath}$. (P-13) $\nu_{b\tilde{\imath}}$

$\sum_{f\in z} q_{fs} - q^{nodal}_{ns} = 0$ for all n and s. (P-5) β_{zs}

Market constraints

$\sum_n \sum_s \tilde{A}_{ns\tilde{\imath}} q^{nodal}_{ns} + \sum_b q^{bank}_{b\tilde{\imath}} = C_{\tilde{\imath}}$ for all $\tilde{\imath}$. (P-14) $\lambda_{\tilde{\imath}}$

Private and side constraints

$\sum_f \sum_s E_{fsg} q_{fs} \le Z_g$ for all g. (P-7) σ_g

The ORAM objective function maximises the joint total benefit from trade to both the farms and the banks. The market constraints are modelled as equalities because the tradable capacity of each constraint $\tilde{\imath}$ is fully distributed among the market participants, ex-post and ex-ante. The set of market constraints includes receptor capacity constraints ($\tilde{\imath} = rt$), source constraints ($\tilde{\imath} = i$), and multi receptor/period constraints ($\tilde{\imath} = j$). The three types of market constraints can be separated as follows.

$\sum_f \sum_{s=\max(1,t-T)}^{\min(t,S)} H_{nr(t-s)} q_{ns} - y_{rt} = 0$ for all r and t. (P-8) γ_{rt}

$y_{rt} + \sum_b q^{bank}{}_{brt} = C_{rt}$ for all r and t. (P-15) λ_i

$\sum_f \sum_s A_{nsi} q^{nodal}{}_{ns} + \sum_b q^{bank}{}_{bi} = V_i$ for all i. (P-16) π_i

$\sum_r \sum_t B_{rtj} y_{rt} + \sum_b q^{bank}{}_{bj} = W_j$ for all j. (P-17) δ_j

The model does not include any private or side constraints that affects the banks, but they can be included if required. The dual formulation of the ORAM is given below.

Minimise $\sum_f \sum_s \sum_k U_{fsk} \theta^+{}_{fsk} + \sum_b \sum_{\tilde{\imath}} \sum_l U^{Bank}{}_{b\tilde{\imath}l} \alpha^+{}_{b\tilde{\imath}l} + \sum_{\tilde{\imath}} C_{\tilde{\imath}} \lambda_{\tilde{\imath}} + \sum_g Z_g \sigma_g$, subject to:

$\theta^+{}_{fsk} - \theta^-{}_{fsk} + \mu_{fs} = P_{fsk}$ for all f, s, and k. (D-1) x_{fsk}

$\alpha^+{}_{b\tilde{\imath}l} - \alpha^-{}_{b\tilde{\imath}l} + \nu_{b\tilde{\imath}} = P^{Bank}{}_{b\tilde{\imath}l}$ for all b, $\tilde{\imath}$, l. (D-6) $x^{bank}{}_{b\tilde{\imath}l}$

$-\mu_{fs} + \beta_{ns} + \sum_g E_{fsg} \sigma_g = 0$ for all f and s. (D-3) q_{fs}

$-\nu_{b\tilde{\imath}} + \lambda_{\tilde{\imath}} = 0$ for all b and $\tilde{\imath}$. (D-7) $q^{bank}{}_{b\tilde{\imath}}$

$-\beta_{ns} + \sum_{\tilde{\imath}} A_{ns\tilde{\imath}} \lambda_{\tilde{\imath}} = 0$ for all n and s. (D-5) $q^{nodal}{}_{ns}$

$\theta^+{}_{fsk}$ and $\theta^-{}_{fsk} \geq 0$ for all f, s, and k.

$\alpha^+{}_{b\tilde{\imath}l}$ and $\alpha^-{}_{b\tilde{\imath}l} \geq 0$ for all b, i, and l.

μ_{fs} free for all f and s.

$\nu_{b\tilde{\imath}}$ free for all b and $\tilde{\imath}$.

β_{ns} free for all n and s.

$\sigma_g \geq 0$ for all g.

$\lambda_{\tilde{\imath}} \geq 0$ for all $\tilde{\imath}$.

As mentioned above, the model allows the banks to buy and sell constraint capacity. But in the succeeding discussions, we assume that the banks are capacity sellers rather than buyers, especially to highlight the effects of the regulator's participation in the market as a capacity owner who offers to sell constraint capacity.

The shadow price $\lambda_{\tilde{\imath}}$ of the market constraint $\tilde{\imath}$ (P-14) indicates the marginal value of constraint capacity. This is a price which matches the market demand and supply for constraint capacity and hence the market price of constraint capacity (constraint price). The farms and the banks should be charged (paid) at $\lambda_{\tilde{\imath}}$ per each unit of constraint capacity bought (sold).

The shadow price $v_{b\tilde{\imath}}$ of the constraint (P-13) which calculates the final capacity position of each bank, indicates how much the objective function would increase if bank b were given another unit of constraint $\tilde{\imath}$. Similar to the farm participant price μ_{fs}, this is also a participant price, indexed to a particular bank and it describes the economic characteristics of the bank.

If bank b is the regulator who offers to sell constraint capacity based on the opportunity cost, ecological cost, and water user's cost of having nitrate in water, the shadow price $\alpha^{+}_{b\tilde{\imath}l}$ of the bid upper bound constraint (P-11) indicates the cost saving from the last unsold (accepted) capacity unit from that bid. Hence if a regulator offer is rejected, $\alpha^{+}_{b\tilde{\imath}l} \geq 0$ (in this gross pool formulation, a bid being accepted is equivalent to an offer being rejected). The shadow price $\alpha^{-}_{b\tilde{\imath}l}$ of bid lower bound constraint (P-12) indicates how much the society would lose if one unit was accepted from that bid, i.e., how much it would cost the society if the regulator was forced to withhold one unit from that bid. Hence, if a regulator's offer is accepted, $\alpha^{-}_{b\tilde{\imath}l} > 0$. If a bid l corresponds to a bank's buy bid, the associated shadow prices of $\alpha^{+}_{b\tilde{\imath}l}$ and $\alpha^{-}_{b\tilde{\imath}l}$ can be interpreted as similar to θ^{+}_{fsk} and θ^{-}_{fsk} discussed in section 7.2 of Chapter 7.

The dual constraints associated with primal variables $x^{bank}_{b\acute{r}l}$ and $q^{bank}_{b\acute{r}}$ produce the price relationship $\lambda_{rt} = v_{b\acute{r}t} = P^{Bank}_{b\acute{r}l} + \alpha^{-}_{b\acute{r}l} - \alpha^{+}_{b\acute{r}l}$. As discussed in section 7.2.4, from duality and complementary slackness we can show that if a bank offer is fully accepted, $\lambda_{rt} \geq P^{Bank}_{b\acute{r}l}$; if an offer is not accepted, $\lambda_{rt} \leq P^{Bank}_{b\acute{r}l}$; and if an offer is partially accepted, $\lambda_{rt} = P^{Bank}_{b\acute{r}l}$. Hence, a bank can be the marginal trader who determines the market price ($\lambda_{rt} = P^{Bank}_{b\acute{r}l}$). The market price of constraint capacity cannot be zero unless the banks all bid at price zero, or not enough bid for the constraint. The market allows the regulator, who offers to sell constraint capacity, to act as a bank, effectively refusing to sell unless the market price is above its bid (reservation) price. Hence, the farms have to bid for loading permits to set the constraint prices above the regulator's reservation price ($\tilde{A}_{ns\tilde{\imath}}P_{fsk} \geq \lambda_{i} \geq P^{Bank}_{b\tilde{\imath}l}$), otherwise the farms cannot buy constraint capacity (i.e., the farms who affect the particular constraint cannot buy loading permits). To buy the total capacity, the farms have to out-bid the highest bank bid. Even if only one farm's year-1 to year-S permits affect some year t, the farm's ability to affect the price is limited because it has to compete with the banks.

If $\tilde{\imath}$ corresponds to a receptor capacity constraint (receptor r in period t), $\tilde{\imath} = rt$, and the farms cannot buy the capacity of receptor r in period t unless they bid so that,

$$H_{nr(t-s)}P_{fsk} \geq \lambda_i \geq P^{Bank}{}_{brtl}.$$

8.4 Benefits of Having Resource Banks in the Market

The ability to charge the polluters appropriately and to balance resource consumption over time is just a few of the benefits of allowing resource banks (mainly, the regulator) to participate in the market and trade constraint rights. Apart from that, the resource banks can improve the performance of the market.

Markets in diffuse nitrate discharge permits generally provide limited opportunities for trade in loading permits because the loading permits are not comparable between farms[40]. As discussed above, loading permits are different compositions of constraint rights (commodities). The ability and willingness of the farms to trade each commodity in the market are limited by the farm's location and the effects on each constraint, which determine the composition of each farm's loading permit. If the farms are hydro-geologically isolated, having effects on unique combinations of constraints, they have limited opportunities to trade with each other. Therefore, when the farms alone cannot create an active market, the resource banks can make a market work. Even if the farms cannot trade with each other, every farm can trade with the banks (multilaterally). Therefore, the resource banks can improve both the market competitiveness and liquidity by acting as "market makers."

For a trading system to be useful in any catchment, the non-tradable sources, mainly the state of the aquifer, should not be bad enough to violate the market

[40] Chapter 12 includes a section on market competitiveness, which discusses the extent to which nonpoint sources can trade with each other.

(environmental) constraints. For example, if the expected nitrate flux into a surface water body via groundwater is above the maximum acceptable level, no capacity is left for trading in the years to come unless the receptors and/or the groundwater aquifer can be cleaned.

If someone can clean nitrates from a receptor, the tradable capacity of the receptor can be augmented. Similarly if someone can remove nitrates flowing from some region, the regional loading cap can be relaxed. Hence the constraint capacity of the market constraints are not always fixed but can be augmented. Those who have the ability to augment constraint capacity can participate in the market as resource banks and sell augmented capacity. Hence, the proposed market model incentivises active cleanup technologies and methods.

Assume a resource bank b that can remove nitrates from a receptor r in year t, up to a maximum of $C^A{}_{rt}$ (kg or mg/l) at a marginal cost of $P^{Bank}{}_{rt}$, submits a single bid tranche of $C^A{}_{rt}$ at $P^{Bank}{}_{rt}$. Then the capacity constraint for receptor r in period t can be re-written as follows to facilitate offering additional capacity to the market.

$$y_{rt} + \sum_b q^{bank}{}_{brt} = C_{rt} + C^A{}_{rt} \qquad \text{(P-18)} \ \lambda_i$$

Since the cost of remediation is relatively high, the farms would not buy augmented capacity unless the currently available capacity (capacity offered to the market by the regulator) is insufficient and the incremental profit from more nitrate intensive farming options justifies paying for polluting the receptors beyond the natural capacity, and paying the cost of cleaning. If the banks try to monopolise the market, the farms will find it more economical to implement on-site nutrient management practices to reduce nitrate losses rather than buying more permits. Then the banks will not be able to recover the cost of building and maintaining the treatment plants.

How a bank optimizes the bids, and the potential for price manipulation by the banks, is beyond the scope of this work. We expect that the regulator will set the bids to price out over-consumption, not to price out the farms entirely and monopolize the market.

8.5 Charging a Penalty on Resource Consumption

In a catchment dominated by agriculture, the farms may oppose the intervention of any third party (bank) in the market because such third parties can affect the prices. On the other hand, the farms may claim that they own permanent rights to discharge nitrates, and oppose the regulator's participation in the market as a capacity owner. In the absence of resource banks, a penalty may be imposed to discourage full consumption of future capacity and to encourage saving for the future. Just like the stepped bank bid functions, stepped penalty functions may be set to price out over-consumption of resources by low value uses. Including the penalties would change the constraint structure of the Generalized OLM and thus the resulting price structures. The constraint structure for a simple penalty function with two steps is given below, assuming no market constraints other than the receptor capacity constraints.

Assume a penalty of zero on the first C^{Free}_{rt} ($<C_{rt}$) units of receptor capacity allocated (kg or mg/l), and a penalty of $P^{Penalty}_{rt}$ (\$) on each unit of capacity allocated above C^{Free}_{rt}. Two receptor end variables for the total allocation of receptor capacity, one without penalty (y^{free}_{rt}) and one with penalty ($y^{penalty}_{rt}$) can be used to model the constraints. The following additional constraints are required to accommodate the penalties.

$y_{rt} - y^{free}_{rt} - y^{penalty}_{rt} = 0$ for all r and t. (P-19) λ_{rt}

$y^{free}_{rt} \leq C^{Free}_{rt}$ for all r and t. (P-20) ψ^{+}_{rt}

$y^{penalty}_{rt} \leq C_{rt} - C^{Free}_{rt}$ for all r and t. (P-21) ρ^{+}_{rt}

$-y^{free}_{rt} \leq 0$ for all r and t. (P-22) ψ^{-}_{rt}

$-y^{penalty}_{rt} \leq 0$ for all r and t. (P-23) ρ^{-}_{rt}

The following dual price relationships are derived from the dual constrains associated with primal variables, y^{free}_{rt} and $y^{penalty}_{rt}$.

$\lambda_{rt} = \psi^{+}_{rt} - \psi^{-}_{rt} = \rho^{+}_{rt} - \rho^{-}_{rt} + V_{rt}$.

If the market clears with surplus penalty-free capacity, i.e., if $0 < y^{free}_{rt} < C^{Free}_{rt}$, then

$\psi^{+}_{rt} = 0$, $\rho^{+}_{rt} = 0$, $\psi^{-}_{rt} = 0$, and $\rho^{-}_{rt} > 0$. Hence $\lambda_{rt} = 0$.

If the market clears at the penalty margin, i.e., if $0 < y^{free}_{rt} = C^{Free}_{rt}$, then

$\psi^{+}_{rt} > 0$, $\rho^{+}_{rt} = 0$, $\psi^{-}_{rt} = 0$, and $\rho^{-}_{rt} > 0$. Hence $\lambda_{rt} = \psi^{+}_{rt} = V_{rt} - \rho^{-}_{rt}$.

If the market clears above the penalty margin but with surplus capacity, i.e., if $0 < y^{penalty}_{rt} < C_{rt} - C^{Free}_{rt}$, then

$\psi^{+}_{rt} > 0$, $\rho^{+}_{rt} = 0$, $\psi^{-}_{rt} = 0$, and $\rho^{-}_{rt} = 0$. Hence $\lambda_{rt} = \psi^{+}_{rt} = V_{rt}$.

If the market clears with full capacity allocation, i.e., if $0 < y^{penalty}_{rt} = C_{rt} - C^{Free}_{rt}$, then

$\psi^{+}_{rt} > 0$, $\rho^{+}_{rt} > 0$, $\psi^{-}_{rt} = 0$, and $\rho^{-}_{rt} = 0$. Hence $\lambda_{rt} = \psi^{+}_{rt} = V_{rt} + \rho^{+}_{rt}$.

If the market clears above the penalty margin, the farms have to pay at least the penalty $P^{Penalty}_{rt}$. If the farms collectively buy the total capacity, they have to pay the penalty plus the price they would have been charged if no penalty were imposed. Again, the penalty should be set to price out over-consumption, not to price out the farms entirely. The environmental authority's problem of optimising the penalty margin and the rate is beyond the scope of this work.

8.6 A Conceptual Market Model for a Typical Lake Catchment

The ORAM presented above is an abstract, generally applicable LP model for a double-sided market which allows the farms to buy (and sell) loading permits and the banks to sell (and buy) constraint capacities. However, the structure may vary depending on the catchment hydro-geology, surface water flow system, and long term goals of the community. This section presents a market model for a hypothetical lake catchment inspired by the nitrate pollution problem in the Lake Taupo catchment[41].

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[41] Lake Taupo is the largest lake in New Zealand. More than 30 rivers and streams flow into the lake, but it has only one outlet, the Waikato River. Since the mid 1970s, increased nitrate levels have been observed in the lake due to intensive farming and urbanization in the catchment. Catchment hydro-geology is complex with groundwater nitrate residence times ranging from 20 to 180 years and varying levels of attenuation in the aquifer. The lake waters move slowly (water, once in Lake Taupo, can take 11 years to move through the lake to the Waikato River). Even without further intensification of land use, the total nitrogen load into the lake is expected to increase in the future, because the catchment groundwater quality has not yet reached equilibrium with the current land use distribution (Morgenstern 2008). To maintain current water quality,

The main purpose is to show how the complex market interactions in a large catchment can be modelled as an LP, sufficiently addressing the underlying physical transport systems while maintaining the simplicity of the model. We do not present a numerical simulation of the model (numerical results for another case study are discussed in the next chapter), but we discuss how the price structure is driven by the constraint structure and the ability of the model to generate theoretically efficient prices. The model does not correspond to any particular catchment, but a general representation of a lake catchment.

We consider a slow-moving lake which has many rivers flowing in and one outlet (Figure 8.1).To develop a conceptual market model, we have to make some assumptions on the underlying hydro-geological systems and the regulatory systems governing permit trades.

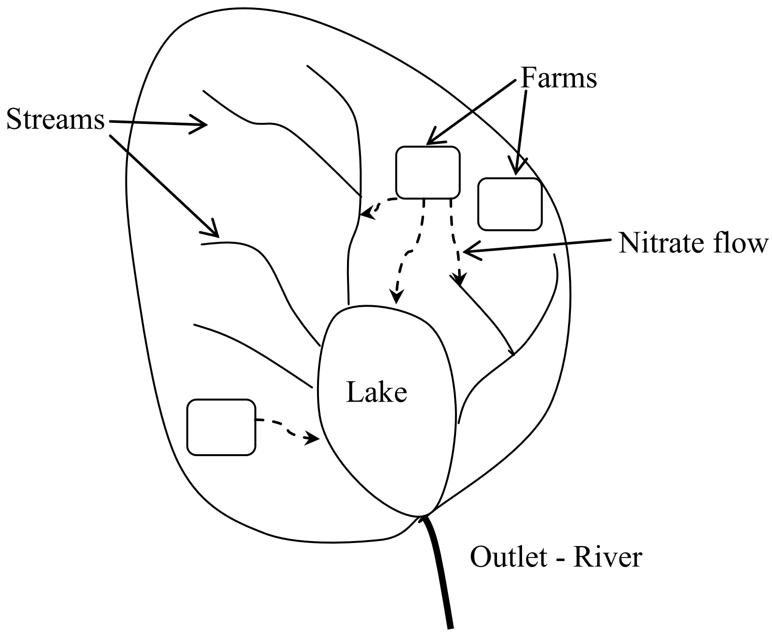

Figure 8.1: Hypothetical Lake Catchment

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the nitrogen load into the lake has to be reduced by at least 20% (Petch et al. 2003). Tradable nitrogen discharge permits have been proposed as a means of achieving the target.

8.6.1 Physical Water Transport System: Assumptions

Nitrate loading permits are traded, assuming that nitrogen loss from farms in the catchment occurs as nitrate leaching (runoff losses are negligible). Nitrate loaded by the farms may be carried down to the lake via streams or direct groundwater seepage. Therefore, the streams and the lake are considered as receptors where the mass of nitrate discharge into each receptor is to be controlled. We assume that in-stream nitrate residence time is less than a year, and the proportions of in-stream nitrate attenuation (loss before reaching the lake) are known. We assume a simple (rough) nitrate mass balance model for the lake. The mass balance model assumes that any nitrate ion in the lake at any time has known probabilities of being lost (by de-nitrification or other processes) and of being drained to the outlet. The hypothetical model is given in Section 8.6.3.

8.6.2 Market Rules: Assumptions

All the farms in the catchment are assumed to be participating in the trading program as discussed in section 6.7.1 of Chapter 6. An independent entity called the "market operator" operates the market. A regional environmental authority called the "regulator" participates in the market as a resource bank which buys and sells constraint permits. Trading takes place once every year.

At the beginning of every trading year, the market operator calculates the available receptor capacities, taking into account all non-tradable sources, including the previous year's discharges. We assume no previously allocated permanent discharge rights, and only pre-purchased permits are considered as initial holdings. All initially free (unallocated) constraint capacity is considered to be owned by the regulator.

8.6.3 Market Modelling

Based on the assumptions, a market model for the catchment requires two types of environmental constraints specifying the ability of the receptors to accept nitrates (restrictions on total nitrate discharge into the receptors in each year) and the ability of the lake to store nitrates (restrictions on annual nitrate storage in the lake) while maintaining its health[42]. The trading program would be simpler if tradable constraint rights are defined only relative to the constraints on annual discharge limits[43]. Hence, we assume that only discharge rights are traded, and the surpluses generated by storage constraints are paid to the regulator. A cap on loading rate per hectare may be imposed (outside the market) to secure local groundwater quality.

For the market constraints, a common index $\tilde{\imath}$ was used in model ORAM because tradable constraint rights were assumed for all market constraints. But in this case, tradable rights are assumed only for the receptor capacity constraints, not for the storage constraints (these are receptor end multi-period constraints). Hence for this model, we do not use the common index $\tilde{\imath}$. Apart from having a single bank participating in the market, the model structure, except the set of market constraints, would be the same as in model ORAM. Hence we present only the set of market constraints.

Additional indices, parameters, and variables:

Receptor $r = 1$ is the lake, and $r = 2, 3, \ldots, R$ are the streams.

y^{lake}_t = total mass nitrate discharge into the lake during year $t = \sum_r E_r y_{rt}$ where $1-E_r$ = proportion of in-stream nitrate attenuation. $E_1 = 1$.

y^{store}_t = mass nitrate storage in the lake at the end of year t.

G^W = proportion of mass nitrate in the lake that flows away from the outlet (river) annually.

G^L = proportion of annual nitrate attenuation in the lake.

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[42] If the nitrate fate and transport in the lake are well understood with certainty, either type of constraints alone may be sufficient to maintain lake water quality. However, under a high level of uncertainty, having both types of constraints is safer.

[43] Another option is having only the discharge based constraints in early years and only the storage based constraints in later years of the planning horizon.

$y^{store}{}_t = G\ (y^{store}{}_{t-1} + y^{lake}{}_t)$ where $G = (1-G^W-G^L)$. This is the lake nitrate balance equation assumed.

C^0 = maximum acceptable mass nitrate storage in the lake.

Model: LakeModel (Market constraints)

Maximum annual nitrate load into the streams

$y_{rt} + q^{bank}{}_{rt} = C_{rt}$ for all r and t. (P`-2) λ_{rt}

Maximum annual nitrate load into the lake

$\sum_r E_r y_{rt} - y^{lake}{}_t = 0$ for all t. (P`-3) ε_t

$y^{lake}{}_t + q^{bank}{}_{1t} = C_{1t}$ for all t. (P`-4) λ_{1t}

Maximum in-lake nitrate storage

$Gy^{lake}{}_t + Gy^{store}{}_{t-1} - y^{store}{}_t = 0$ for all t. (P`-5) δ_t

$Y^{store}{}_t \leq S_0$ for all t. (P`-6) $\lambda^0{}_t$

8.6.4 Price structures and Relationships

All the market constraints in this model are receptor based. Since the model contains both multi-period and multi-receptor constraints, prices should be spatially and temporally dependent. The constraint structure of the model provides the following price relationships.

$v_{rt} = \lambda_{rt}$ for all r and t.

$\gamma_{rt} = E_r\varepsilon_t + \lambda_{rt}$ for $r = 2,3, \ldots, R$ and all t.

$\gamma_{1t} = \varepsilon_t$ for all t.

$\varepsilon_t = \lambda_{1t} + G\delta_t$ for all t.

$\delta_t = G\delta_{t+1} + \lambda^0{}_t$ for all t.

Price λ_{rt} for some $r \in [2,3, \ldots, R]$ is the market price per unit nitrate discharge into stream r in year t. The market price per unit nitrate discharge into the lake in year t is λ_{1t}. The regulator which participates in the market as a bank (possibly as a resource owner) will be selling at λ_{rt}. However, the prices charged to the farms, γ_{rt} may be higher than λ_{rt} because discharges into the streams have effects on the lake also. For the farms, the stream price equals the stream's market price plus the lake price adjusted by the proportion of in-stream nitrate carried down to the lake ($\gamma_{rt} = E_r\varepsilon_t + \lambda_{rt}$). Thus, even if the farms in a sub-catchment perform well below the maximum nitrate intake capacity of the local streams, they may face a high price because a relatively large proportion of their discharges flow down to the lake. The farms may face an even higher price if the local constraints also bind.

The storage cost (cost of carrying a kg of in-lake nitrate into the next year) is δ_t. For discharging nitrate into the lake, the farms should pay the expected cost of carrying forward in addition to the market price ($\varepsilon_t = \lambda_{1t} + G\delta_t$). The storage cost of each year is determined by current and future storage capacity constraints ($\delta_t = G\delta_{t+1} + \lambda^0{}_t$). Even if the total discharge into the lake in some year t is well below the maximum acceptable level, the price of discharge in year t may be increased by the capacity shortages expected in the future. In large agricultural catchments, due to unmanaged nitrate discharges in the recent past, capacity shortages are more likely to occur in the future than in the present. For example, in the Lake Taupo catchment, a large amount of nitrate leached from current and previous land use is currently flowing towards the lake via groundwater, and nitrate discharge into the lake from this non-tradable source is likely to increase in the future (Morgenstern 2008). The above price structure has the capability of pricing the current discharges to reflect the value of future capacity.

8.7 Discussion and Conclusions

In the two preceding chapters (7 and 8), we presented alternative linear programming models to price diffuse nitrate discharge permits. The simplest model simulates a market in loading permits where the diffuse dischargers, mainly agricultural dischargers, trade rights to load nitrates into groundwater aquifers. Environmental constraints are imposed on maximum acceptable nitrate level in groundwater and groundwater fed surface water bodies. The model generates self-explanatory and consistent resource (commodity) prices from which the permit prices can be derived.

In addition to the essential capacity constraints, catchments can have different types of receptor-based or source-based constraints, and these constraints differentiate nitrate permit markets from other general permit markets. Most importantly, additional receptor based constraints may be required to describe nitrate residence and transport in surface water bodies. Including such constraints in the market clearing LP models has significant effects on market prices. One major consequence of such constraints is settlement surpluses, and hence the market design should include mechanisms to deal with the prices associated with these constraints.

Ultimately, what prices should be charged is a matter of which environmental resources and services are traded in the market. Once all demand and supply constraints on all resources and services are included in the market clearing LP, the proposed generalized market models may be implemented as a combined market for any number of inter-dependent and inter-related commodities.

We showed that a single sided buyers' market in loading permits can lead to premature consumption and under pricing of resources. On the other hand, loading permits are not comparable between farms and hence they provide limited opportunities for trade. Therefore, we proposed an expanded market model which allows the polluters to buy loading permits and environmental (or public) agents to sell (or lease out) the ability of the natural water systems to accept and dilute nitrates (as constraint rights). Market participation of such third parties, mainly the environmental authorities who represent the public interest, can balance resource consumption over time, increase market competitiveness and aid liquidity. In case third parties cannot participate in the market, other mechanisms such as penalties on over-consumption could be applied to balance resource consumption over time and to discourage over-consumption of receptor capacities by low value uses.

Chapter 9

9 Participant Decisions

9.1 Introduction

This chapter provides guidance for the market participants on how they can use the available information to optimise their behaviour in the market. We do not present any participant-side optimisation models, but discuss the important considerations.

We first present the factors that affect the decisions of agricultural nonpoint sources. We discuss the models and information that would be useful to the farms in optimising their bids. We specifically highlight the relationship between the profitability of different land use options and the value of loading permits. We then discuss the factors that affect the regulator's behaviour in the market, assuming that the regulator is a public agent, rather than a profit seeking business agent. We discuss the issues that arise in determining the present value of future capacity. We show how the available receptor capacities would restrict the regulator's decision space.

9.2 Information Required by Agricultural Nonpoint Sources

Since this work is mainly focused on agricultural pollution, the major players in the market would be the commercial farmers in the catchment. The size of the nitrate loading permit held by a farm in any year determines the maximum allowed nitrate loading into the groundwater system from that farm. However, the farms cannot directly control nitrate loading. The amount of nitrate loading depends on the land use, weather, and geography. What the farms can control is the land use. Therefore, the size of the nitrate loading permit held by any farm in any year determines the type of “land use” the farm can adopt in that year.

A “land use option” is a combination of factors such as the type of crop grown, type of stock, fertilizer application rate, stocking density (for example, cows per hectare), irrigation method, effluent discharge system, drain layout, and other farming and land management practices. The size of the permit required to adopt some land use option (for example, to farm a dairy with a stocking rate of 2.8 cows per hectare, and with a recommended effluent discharge system), is the estimated nitrate leaching from that land use option.

The options available for the farms are limited. The major factors that affect the nitrate leaching rate, such as fertilizer application rate and stocking rate, are also the major factors that affect profitability. Hence a rational farm would bid for loading permits based on the potential nitrate leaching and profitability of alternative land use options. To optimize the bids, the farms need to know both the economic and environmental effects (profits and nitrate loading) of each land use option.

9.2.1 Soil Nitrogen Models

The farms can use soil nitrogen models to estimate the potential nitrate leaching from alternative land uses. Standard computer-based soil models such as SWAT and GLEAMS and regionalized nutrient budget models such as OVERSEER can simulate soil nitrogen dynamics and estimate nitrate leaching from different land use scenarios, as discussed in Chapter 2.

The computer models usually estimate the potential nitrate loading as a rate in kg per unit area per year (kg/ha/year). Then the land users have to multiply the loading rate by the farm size to obtain the size of the permit required. This calculation is based on the assumption that nitrate loading occurs uniformly over the whole area of each farm. If the farms can prove to the authorities that loading occurs only in a part of the farm area, the size of the permit required may be adjusted accordingly.

The models used to estimate leaching could be authorized by the market authorities. If the farms do not have access to such models, the market authorities could provide information about leaching from alternative land use options and their permit requirements. In any case, accountability and liability issues will be raised, if the models and/or information were subsequently revised. Different authorities might take a different view as to whether the participants should then be deemed to have purchased permits for the agreed discharge rate, or for the activity level that, according to the model, was expected to produce that discharge rate. Who is liable for the consequences of wrong estimates, is an issue to be resolved before a trading system is implemented.

9.2.2 Farm Economic Models

Farms also need to know the potential profit from alternative land uses. Farm economic models, for example, WFM (Beukes et al., 2005), estimates the potential profits from different land use and management options. In New Zealand, the Ministry of Agriculture and Forestry (MAF) publishes annual reports on the production and financial outcomes of the farms in different agricultural sectors (dairy, sheep/beef, horticulture, and etc.) and regions throughout New Zealand. Such information and models can also be used to estimate the profitability of different land use options.

Rather than independent agro-ecological and agro-economic models, integrated agro-ecological and agro-economic models which can predict both the nitrate losses and potential profits from alternative land uses would better help the farms in optimizing their bids. Such integrated models are rare but do exist, for example, the models proposed in Johnson, Adams and Perry (1991) and Mohamed, Sharifil and Keulenz (2000).

9.2.3 Best Management Practices

Nitrate loading may be negligible from those land uses which employ best nutrient management practices. Recommended management practices include nutrient budgets to minimise nitrogen losses, and feed pads and herd homes to capture livestock effluents and urine (Thiagarajah Ramilan, 2008). Farms holding small permits (or no permits) can adopt those best management practices to minimise nitrate loading. The responsibility of identifying the best management practices, based on the regional soil geography and climate, will remain with the government or the regional environmental authorities. These authorities may specify the minimum levels of management practices required to operate without a nitrate permit.

9.3 How Do Farms Determine the Optimal Bids?

Using the above discussed agro-economic and agro-ecological models, the farms can calculate the profitability of each land use option and the size of the loading permit required for each land use option. Usually, if nitrate loading comes free, more nitrate intensive farming options such as dairying are more profitable. Once the farms know the profitabilities and permit requirements of alternative land uses, they can decide how much each additional 1 kg or each additional block (x kg) of nitrate loading is worth, and hence how much they are willing to pay for each additional unit or block of nitrate loading.

For example, assume a crop farm X has three land use options, crop A, crop B, and crop C, with expected annual profits of \$500, \$800, and \$1000 respectively. The potential annual nitrate leaching from A, B, and C are 10 kg, 20 kg, and 40 kg respectively. Assume that the farm cannot affect the market prices, but can buy 10 kg, 20 kg, 40 kg or none.

Given all costs of farming other than the cost of nitrate permits are accounted for in calculating the above profit figures, the value of the first 10 kg of nitrate loading is \$500 for farm X. If the farm is required to pay for nitrate loading, the maximum amount of money it would like to pay for the first 10 kg is \$500. The value of each 1 kg is \$50, assuming profit from a given land use is proportional to loading.

If the farm could buy another 10 kg, it could make an additional profit of \$300 by shifting to land use option B. Hence, the next 10 kg of nitrate loading is worth \$300 to farm X. The farm would pay a maximum \$30 each for the next 10 kg. Similarly, farm X would pay a maximum of \$10 each for the next 20 kg of nitrate loading. The results may be given as a stepped marginal profit (value) function, as in Figure 9.1 below.

Therefore, for the above simple example, the optimal bids are 10 kg at \$50, 10 kg at \$30, and 20 kg at \$10. They indicate the maximum price the farm would like to pay for each block, or the minimum price at which the farm would sell each block. The blocks may correspond to different crops, different stocking rates, different fertilizer application rates, or different combinations of those. Hence, a step in the marginal profit function would possibly correspond to a type of land use.

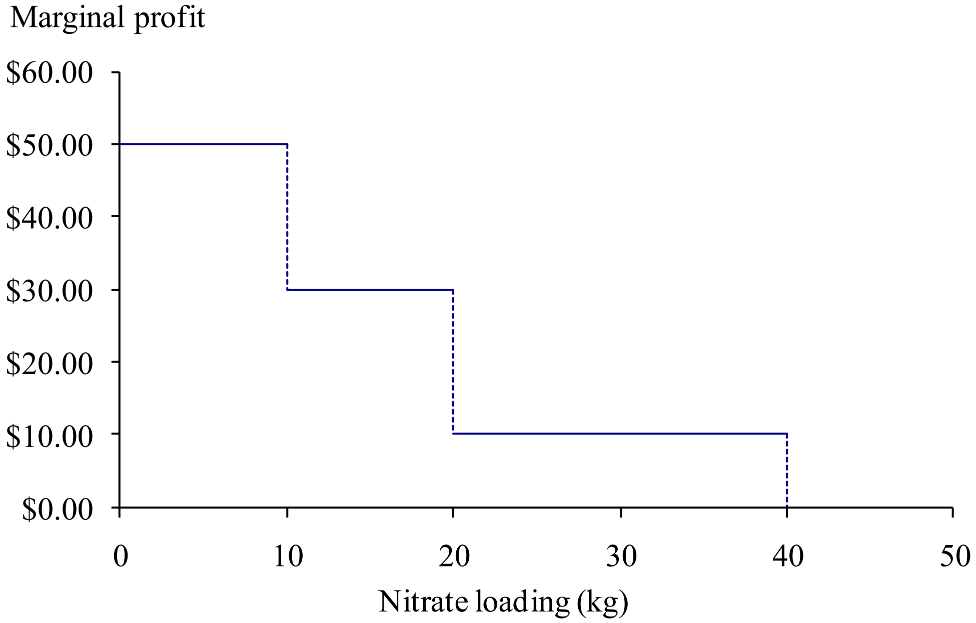

Figure 9.1: Stepped marginal profit function of Farm X, for nitrate loading.

The example discussed above is just a simplification of the economic theory related to marginal economic gains. A farm’s true marginal profit function of nitrate loading may not be a stepped piece-wise linear function as above. In reality, the first few units may be worth nothing because commercial farming may not be profitable below a certain scale. For example, growing some crop may not be profitable without applying sufficient amounts of fertilizer, and having a dairy farm may not be profitable without a minimum stocking rate. On the other hand, the profit from any kind of farming may be neither proportional nor linearly related to nitrate loading. A farm’s marginal profits function would generally look like the one given in Figure 9.2.

The stepped bid function we considered above is a stepped piece-wise linearization of a part of the marginal profit function which lies between q^1 and q^3. We effectively assume that unless the farms are allowed to specify a minimum permit level, they will set the bids so that they will be able to deal with the situation if the LP solution allows them to buy less than q^1. The way the farms determine the stepped bid tranches (piece-wise linearization of the function) depends on many private factors. The price they offer for each tranche depends on their risk perceptions and the market regulations such as the maximum number of bids allowed, and whether the conditions like minimum permit levels are accepted by the market.

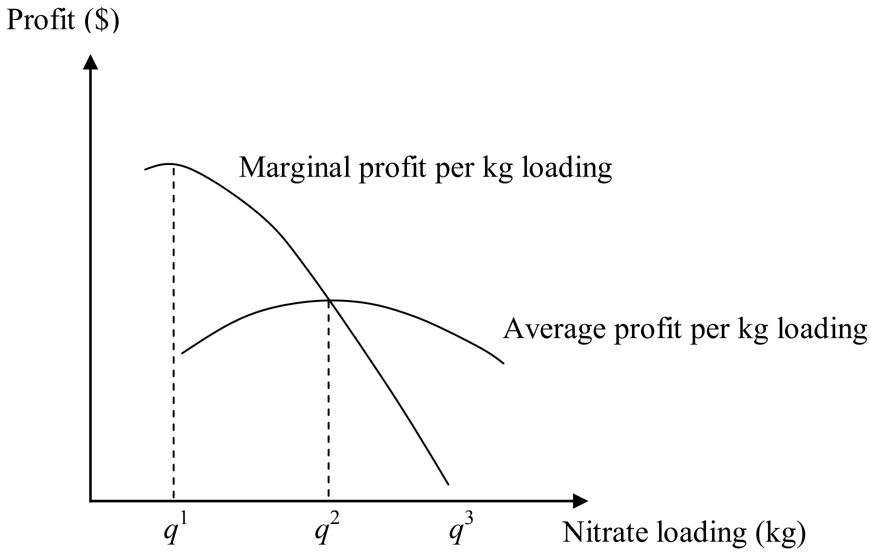

Figure 9.2: Marginal profit of nitrate loading.

Apart from the marginal profit functions, the farm behaviour in a real-time nitrate permit market will be affected by other factors such as market power and strategic intents. Lack of real data collected from the history of a market compels us to assume that the farms would bid based on the marginal profit functions. Still, generally applicable farm profit functions are hard to obtain.

For this work, we assume three bid functions for three types of land uses (dairy, sheep/beef, and crop) as given in Table 9.1. A marginal profit function and a corresponding bid function for each land use type were developed (roughly) based on the “gross $:N relationships”, presented by Woods et al. (2004) (Table 9.2). Those relationships have been estimated specifically, considering the farms in the Waikato region of New Zealand, and therefore they may not be generally applicable.

	Dairy		Sheep/beef		Crop	
Bid	Quantity	Price	Quantity	Price	Quantity	Price
1	13 kg	$41.00	9 kg	$70.00	110 kg	$28.45
2	8 kg	$33.00	3 kg	$48.00		
3	20 kg	$25.00	3 kg	$30.00		
4	19 kg	$21.00	8 kg	$18.00		
5	30 kg	$18.00	19 kg	$6.00		

Table 9.1: Bid functions for different land use types. Dairy, sheep/beef, and crop bids were calculated based on the gross $:N relationships (Table 9.2) for dairy, intensive sheep and beef, and process vegetables, respectively.

Land use type	Nitrate leaching (kg/ha/year)	CFS[44] ($/ha/year)
Dairy	$7.6 \times cows^{1.785}$	$729 \times cows - 235$
Intensive sheep and beef	$1.53 \times e^{(0.2057 \times su)}$	$1114 \times Ln(su) - 1347$
Process vegetables	110	3130

Table 9.2: Gross $:N relationships for Waikato farms, Source: Woods et al. (2004). cows = cows per hectare and su = stock units per hectare.

In Chapter 10, we use the bid functions in Table 9.1 to demonstrate the outcomes of the proposed LP models (prices and allocations), assuming that the proposed market mechanism was applied to allocate nitrate permits in a small catchment area (not in the Waikato Region).

The calculations performed to draw the marginal profit functions are described in Appendix C (only for dairy farms). The tranches were arbitrarily selected to fit the

[44] Cash Farm Surplus (CFS) is the remainder after farm working expenses, but before interest, leases, wages of management, and capital expenditure. Hence, CFS is the operating profit taking into account variable cost, but not the fixed cost.

marginal profit functions. Bid prices were set assuming that the land users are risk averse. The appendix provides an overall view of how to use the available information to estimate the bids.

9.4 How Does the Regulator Set Offers?

If the regulator owns the currently available receptor capacities on behalf of the public, it has to set an offer curve for the receptor capacities, indicating how much each unit (or block) of capacity is worth to the public. Then the regulator's valuation of receptor capacity would be determined by the cost of forgone future opportunities (opportunity cost of being unable to discharge nitrates in the future), the ecological and water users' cost of having nitrate in water, and the cost of any required remediation and treatment.

The problem of estimating the present value of future capacities over a long planning horizon (possibly several decades) is complicated by economic, political, and environmental uncertainties. Risks associated with climate change, interest rates, technological changes, and government policies may affect the present value of future environmental health. Estimation of the social marginal value curves for future capacity is strictly beyond the scope of this thesis. We assume that the regulator would set the offers based on an expected allocation plan which reflects the above costs.

For example, if the capacity of a lake is 1000 kg and 600 kg of nitrate already in groundwater is expected to reach the lake in year 2015, then 400 kg of the lake capacity of 2015 is currently available (assuming no previously allocated loading rights). Out of the 400 kg, the regulator may wish to allocate only 80 kg in each of the trading years from 2011 to 2015, unless the demand is extremely high. Then the regulator can offer the first block of 80 kg at a lower price (\$0.5) so that it is allocated any way, the next block at a relatively higher price (\$40) so that it is allocated only if the demand is relatively higher, and an extremely high price (\$200) on the next block so that it is not allocated unless the demand is extremely high, and like-wise.

For our demonstration in the next chapter, we assume that the regulator sets a single reservation price for the capacity of each receptor and each year (or for the capacity of each constraint), based on the capacity expected to be allocated and the forecasted demand. Since the market allows some trial rounds, the regulator can iteratively adjust the reservation price until the total allocation is acceptable.

Even though we do not present a specific model for the optimisation of the regulator's bid function, we next discuss the possible scenarios of available capacity which is the critical factor that determines the regulator's capacity positions and thus the regulator's behaviour in the market.

9.5 Available Capacity and Tradable Capacity

If the natural hydrological systems do not significantly change over time[45], the major factor which causes temporal variations in capacity availability is the current status of the groundwater aquifer. The current distribution of nitrate concentration in groundwater is mainly a consequence of current and previous land uses in the catchment. As we discussed earlier, nitrate currently in groundwater may flow through a groundwater well or may reach a surface water body decades later. Hence, even if no more nitrate discharges were allowed in the catchment, either from point or nonpoint sources, nitrate level at the receptors may still increase. Therefore, both the feasibility of a market, and the capacity available to a market, are determined by the current state of the aquifers.

Currently *available capacity* of some receptor *r* in some future period *t* (C^{0}_{rt}) may be calculated as follows.

C^{SD}_{r} = sustainable receptor capacity or load standard (kg or mg/l). C^{SD}_{r} indicates the amount of nitrate that a receptor can sustainably accept and dilute in any period.

C^{GW}_{rt} = capacity already committed for groundwater nitrates (kg or mg/l). C^{GW}_{rt} indicates how much the mass nitrate load into a surface water receptor or the nitrate

[45] The ability of a water body to accept nitrates may vary over time due to the variations in temperature, rainfall, and water use. Despite these possibilities, nitrate load standards have been developed for large water bodies such as rivers and lakes (ignoring the effects of climate change), for example TMDLs in the US, and the Lake Rotorua nutrient targets.

concentration in a groundwater receptor would increase in each period, even if there were no more nitrate discharges in the catchment from any natural or non-natural source.

C^N_r = capacity allocations for unmanageable sources other than groundwater (kg or mg/l). C^N_r indicates how much the nitrate level at receptor r is expected to increase in any period t due to minor unmanageable sources such as rain water and natural habitat. If the length of each period t is sufficiently long to cover a whole hydrological cycle (at least a year) or many cycles, C^N_r can be considered as fixed over t, therefore C^N_r is not indexed over t.

C^0_{rt} = currently available receptor capacity (kg or mg/l), how much more nitrate the receptor can take from the manageable (tradable) sources.

$C^0_{rt} = (C^{SD}_r - C^N_r) - C^{GW}_{rt}$.

If there are no previously purchased permits (if S = 1 or if the farms have not purchased future permits from the previous auctions), at the beginning of any trading year (t=1), the regulator's capacity positions are described by C^0_{rt}. Unless the receptor capacities are augmented, the tradable capacity cannot be more than C^0_{rt}. Possible scenarios for C^{GW}_{rt} and C^0_{rt} relative to the sustainable receptor capacity C^{SD}_r are shown in Figure 9.3. Actual shapes of the graphs may be different; the sketches are illustrative.

In an agricultural catchment, if the same land use distribution has continued for a long time (close to the maximum nitrate residence time in the catchment), and thus nitrate leaching has occurred at the same rate, groundwater nitrate concentration, and hence the mass nitrate flux from the catchment, would be in equilibrium with the current land use. In this case, the committed capacity of the receptors may decrease over time as described by scenarios A1 and A2. If the system has not yet reached equilibrium (for example, if the upper catchment land use has recently intensified), the committed capacity may keep on increasing for some time as described by scenarios B1 or B2. The possible distribution of available capacity under each of the committed capacity scenario is shown in Figure 9.4.

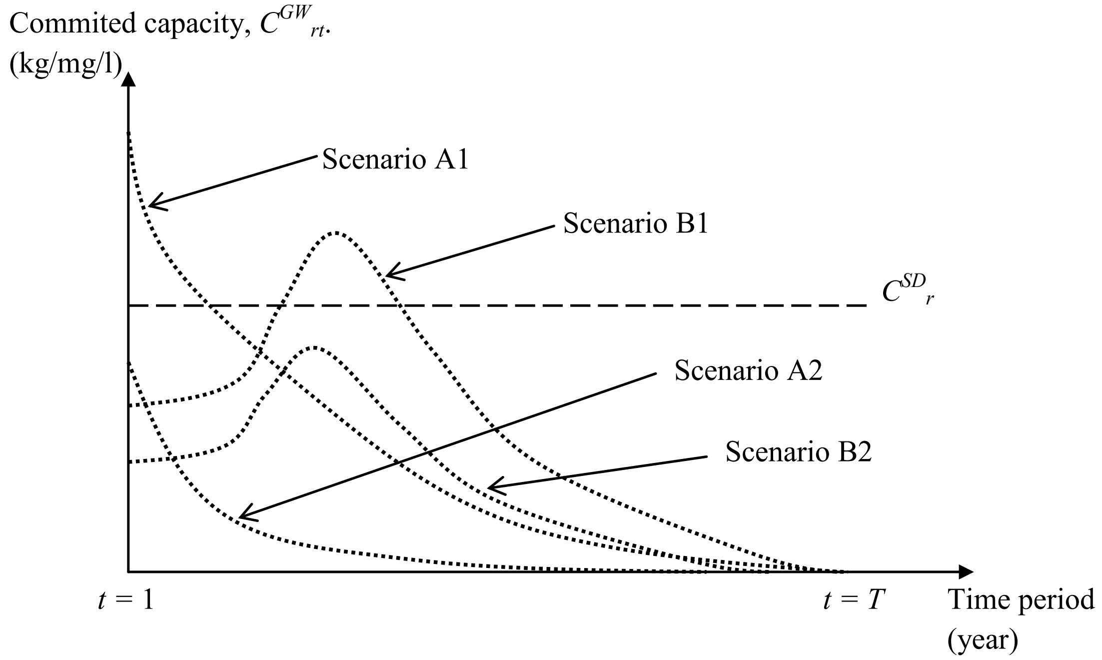

Figure 9.3: Capacity committed for nitrate already in groundwater.

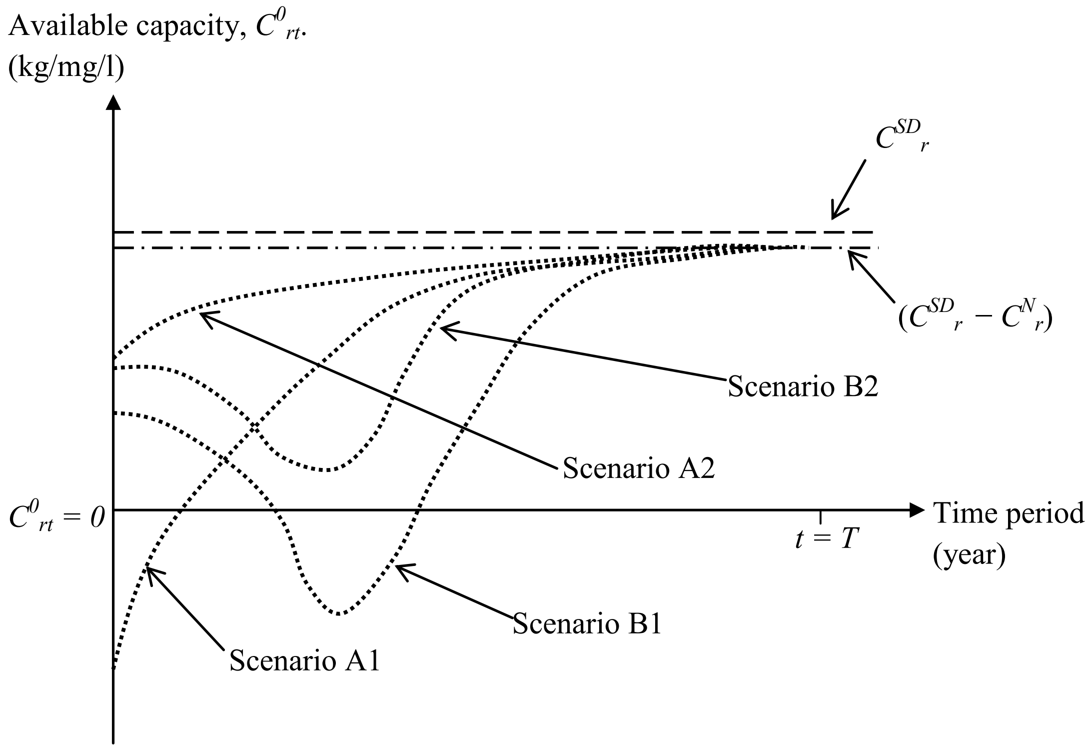

Figure 9.4: Possible scenarios for available receptor capacity.

Under scenarios A2 and B2, some amount of each year's receptor capacity is currently available. The regulator could release the total available capacity to the market (C_{rt}=C^0_{rt}) as a stepped offer function, setting the reservation prices based on the associated costs and the expected allocation schedules.

If the receptor capacity were already over-utilized as in scenarios A1 and B1, no receptor capacity would be available in some years. If the tradable capacities of those years were set to zero, some of the farms might not be able to buy any permits, and might have to shut down their operations for some time. However, if the situation were not that bad, the water system was still in good condition, and the over-loading had taken place only for a few years, the regulator may temporarily relax the sustainable limits based on a timeline to achieve the standards. In this case, the regulator can set reservation prices to cover the cost of treatment and remediation. Otherwise, the regulator can allow third parties to artificially increase the available capacity via treatment and remediation, and participate in the market directly to sell augmented capacity. Then such third parties would play an important role in the market to determine the market prices. In Chapter 10, we demonstrate the market for two available capacity scenarios similar to A1 and A2.

Chapter 10

10 Outcomes of Trade: Prices and Allocations[46]

10.1 Introduction

This chapter explains the outcomes (prices and allocations) produced by the LP models proposed in Chapters 7 and 8, assuming that the market mechanism proposed in Chapter 6 is applied to allocate nitrate loading permits among a set of hypothetical farms in part of the Mataura River catchment in the Southland region of New Zealand. For this purpose, we use a nitrate transport simulation model of the Edendale aquifer which underlies the catchment area[47]. The simulation model has been developed previously by AquaFirma Ltd, for the Southland Regional Council (Rekker, 1998).

The model simulates nitrate-N loading from agricultural properties in the region and the resulting nitrate-N levels in the receiving water bodies; hence, we present our

[46] The results discussed in this chapter are based on the catchment example discussed in Appendix D. Similar analysis was carried out in Prabodanie and Raffensperger (2007), Prabodanie et al. (2009) and Prabodanie et al. (2010) using hypothetical catchment examples.

[47] The proposed trading program works best for a whole catchment rather than for a part of a river catchment. However, since the available nitrate transport model covers only a part of the Mataura River catchment, we demonstrate the results assuming that only the (hypothetical) agricultural sources in the particular area are included in the trading program.

results also in terms of nitrate-N[48]. Information about the original model, and the assumptions and modifications we made to use the model for our purpose, are discussed in Appendix D. Apart from the physical model, all the information used in the demonstrations, and thus the results, are hypothetical and not related to any farm or institution in the region.

We discuss the results of trading under a set of scenarios differentiated from capacity availability over time, constraints applicable, bidding behaviours, types of participants, and trading rules (for example, the number of years for which permits are traded). We demonstrate the resulting prices, allocations, and financial flows, assuming no previously allocated long term (or permanent) loading rights.

Later in this chapter, we consider the presence of permanent loading rights and discuss the importance of making some free initial allocation among the farms based on permanent loading rights or some other criteria. After demonstrating the outcomes of trade in the presence of initial allocations made based on prior land use (permanent loading rights), we discuss the issues related to setting the initial positions and present ideas for further investigation.

10.2 OLM Results

Trading Scenario 1: To demonstrate the results generated from the OLM, this scenario considers the tradable capacities in the 4th column of Table D.4 calculated based on the sustainable land use scenario discussed in Appendix D. Trading takes place at the beginning of year 2011, for the first time. Farms are allowed to bid for loading permits for the next five years ($S = 5$). All dairy farms submit the same set of "Dairy bids", all sheep and sheep/cattle farms submit the same set of 'Sheep bids" and all other farms submit the same set of "Crop bids" given in Table 9.1 of Chapter 9. Each farm submits the same set of bids for each year from 2011 to 2015, ignoring the effects of discounting.

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[48] Nitrate-N (NO_3-N) mass × 4.43 = Nitrate (NO_3) mass. Hence the results for nitrate-N can be converted to nitrate by multiplying by 4.43.

No permanent (or long term) loading rights are present. Receptor capacity is fully owned by the regulator. Since this is the first time trading takes place, farms have no initial permit holdings. Only receptor capacity constraints are present, no multi-receptor/period constraints, no source constraints, and no private or side constraints are present. An AMPL formulation of the OLM is given in section E.1.1 of Appendix E. Since the farms all submit bids in kg/ha/year, the program immediately converts them to kg/year, but displays the resulting allocations in kg/ha/year and the prices per kg, so that the prices and allocations are comparable between farms.

The results for the set of bids are given in Tables E.1, E.2 and E.3. The capacity constraints are binding for years 2012 to 2016, 2018, and 2019 (Table E.3). Upstream farms with relatively longer delay times (for example, farms 1, 2, 3, 9, 11 and 12) get all they bid for at price zero, because their (2011 to 2015) permits do not affect the binding constraints (Tables E.1 and E.2). Permits are allocated only until 2015 but the allocation binds the capacity constraints of later years: 2016, 2018 and 2019. As a consequence, unless the farms which bought permits from the 2011 auction offer to sell back in the consequent auctions, in 2016, the farms having $H_{f10}>0$, $H_{f12}>0$, or $H_{f13}>0$ (44 farms out of 62) will not be able continue any land use which requires nitrate loading permits. This demonstrates the two major issues in the OLM discussed in Chapter 7. Hence we next move onto the ORAM.

10.3 ORAM Results

We discuss ORAM outputs for different sets of regulator offers and farm bids, different sets of constraints, different available capacity situations, and different market rules.

Trading Scenario 2: The regulator, who owns the total available capacity, participates in the market as a bank. The available capacities are as given the 4th column of Table D.4 based on the sustainable land use. The regulator offers the total available capacity of each year to the market with a single reservation price on each year's capacity, a relatively lower price for the first S years to fully allocate the available capacities ($1 on each kg of the years 2011 to 2015 capacities), and a relatively high price on the later years to partially allocate the available capacities ($25 on each kg of the years 2016 to 2064 capacities). The farms submit the same set of bids as considered for scenario 1. An AMPL formulation of the ORAM is given in section E.2.1 of Appendix E. The resulting prices and final allocations are given in Tables E.4, E.5, and E.6.

The results indicate that the final allocations to most of the farms are less, and the nodal prices are higher, but the price distribution is smoother (differences are smaller) compared to the OLM results. No farm can buy at price zero. The receptor capacity prices (Table E.6) for all years other than for years 2012 to 2016 are determined by the regulator's reservation price. Farm demands for the capacity of years 2012 to 2016 are higher and they set the associated prices above the regulator's reservation price to buy the total capacity. The full allocation of the capacity of the first five years may not be a problem because the farms buy permits for the first five years, but the full allocation of 2016 capacity has the consequences discussed under the OLM results. Hence (if this were a trial market) the regulator may raise the reservation price for 2016 capacity to avoid full allocation.

Trading scenario 3: This scenario assumes that the regulator raises the reservation price of the 2016 capacity to $40. This is the only difference from scenario 2. The regulator's reservation price for the capacity of years 2011 to 2015 is still $1, and for the years 2017 to 2064 is still $25. The farms submit the same set of bids considered for scenario 1. The resulting prices and allocations are given in Tables E.7, E.8, and E.9. This scenario allocates only 58,547 kg of the available capacity (61,830 kg) of year 2016 to the farms. The payments due from the farms for buying loading permits, and the payments due to the regulator for selling receptor capacities, are calculated in Table E.9. The total payment made by the farms for loading permits approximately equals the total payment due to the regulator for selling receptor capacity rights. Total benefit from trade is $152,709,597.

Nitrate loading from each farm until 2010 (before the trading program begins) is listed in Table E.7 to the left of the final allocations for years 2011 to 2015. A comparison of the loading permit allocations via trading and pre-trade loading positions indicates that some farms will have to change their land use type significantly as a result of the trading program (for example, farms 3, 58 and 52). The farms may face difficulties in making such dramatic changes immediately.

Trading scenario 4: To avoid or reduce the burden of immediate land use changes, some side constraints may be imposed on allocation so that the farms get at least 80% of the initial (until 2010) permit position in 2011, at least 60 % in the next year, …, and at least 10% in 2015 to allow the farms to gradually change the land uses. Such constraints cannot cause infeasibility because the sustainable receptor capacities and the available capacities were calculated based on the pre-1998 land use distribution which was assumed to have been continued until 2010. This scenario considers the above set of side constraints (together with the receptor capacity constraints) and the same set of bids and offers considered for scenario 3. The resulting allocations after imposing those side constraints are given in Table E.10. The set of side constraints cause a minor (0.06%) reduction in the total benefit from trade (the total benefit from trade is \$152,622,123 for this scenario compared to \$152,709,597 for scenario 3).

Under all the above trading scenarios, the receptor capacities of the early years are fully allocated among the farms. Only a small amount of the receptor capacities of the tail years are allocated among the farms (Table E.9). The next scenario is designed to study what happens if the demand for the capacity of tail years were increased significantly.

Trading scenario 5: This scenario assumes that the bid prices of all the farms having tail effects ($H_{fr(t-s)} > 0$ towards the tail of the planning horizon) were increased significantly. The bid prices of the farms having $H_{frd} > 0$ for $d \geq 22$ were increased to \$1000. These are the farms whose 2011 to 2015 permits affect the years after 2037 (farms 1 to 14, 17 to 21, 23, 24, 25, 28, and 42). The regulator submits the same set of offers considered for scenario 3. The resulting prices and allocations for the changed set of farm bids (without any side constraints) are given in Tables E.11 and E.12.

The results indicate that even if the bid prices of all the farms that affect the receptor in the years after 2037 were drastically increased, the farms cannot buy the total capacity of those years (after 2037). The top bidders of course buy all they bid for, but neither the capacity prices nor the allocations increase significantly compared to scenario 3 results in Table E.9. Hence, if the capacity constraints of the earlier years are tighter than those for the later years as in available capacity scenarios A1 and A2 discussed in Chapter 10, the prices and allocations are driven mostly by the capacity constraints of the earlier years, and hence the tail constraints may be redundant. The long skewed tails of the nitrate transport profiles (as shown in Figure 5.3) also suggest that the effects on the tail of the planning horizon can be ignored. Hence, the length of the planning horizon may be reduced significantly, because the farms cannot buy the capacity of the tail years unless they buy the capacity of the earlier years.

10.4 Model ORAM Results with Multiple Resource Banks

The results discussed above were based on the available capacities calculated assuming sustainable land use until 2010 (until the trading program begins). However if the prior land use was too intensive, the available capacities will be lower or may be zero for some years. For the next trading scenario, we consider the available capacities calculated based on an intensive land use scenario (column 5 of Table D.4).

Trading scenario 6: The regulator who owns all the available capacity participates in the market. However, for the first four years (2011 to 2014), the regulator has no capacity to sell. Another third party called the "supplier" participates in the market as a bank. The supplier has the capability to remove nitrates in the receptor (river) up to a limit of 75,000 kg in each of years from 2011 to 2015 at a marginal cost of $30 per kg, and offers to sell capacity at this marginal cost. The regulator does not submit any offers for the first four years. It offers to sell the total capacity of the fifth year (2015) at $1 and the capacity of all the other years at a price of $25.

An AMPL formulation of the ORAM with multiple banks offering to sell at a single reservation price is given in section E.3.1 of Appendix E. The prices and allocations produced by the model are given in Tables E.13 and E.14. The receptor capacity prices of the early years are determined by the marginal cost of remediation (Table E.14). As discussed above, the demand for the capacity of year 2016 is so high that the farms buy the total available capacity from the regulator.

Compared to the previous results, the final allocations to the farms (Table E.13) are lower, which is reasonable because the available capacities are lower. The farms which have immediate effects on the river, mainly those with peak effects in the tight years (for example, farms 61, 57, and 58), cannot buy any permits for the next few years. To enable them to buy permits, the capacity constraints may be relaxed to some extent, based on a time line by which the accepted quality levels have to be achieved. For example, the capacity constraints of the next 10 years may be relaxed (2016 capacity by 50%, 2017 capacity by 40%, …, and 2020 capacity by 10%) to gradually reduce pollution and achieve the acceptable level over the next 10 years. Still, some farms may not be able to buy permits for some years.

All the above scenarios considered trading permits for five upcoming years. The outcomes of trade would be different if permits are traded for more or fewer years. Due to the capacity shortage in the earlier years (under scenario 6), loading permits can be allocated via trading only for the upcoming year 2011 (S=1), at least until some improvement is achieved.

Trading scenario 7: This trading scenario assumes that permits are traded only for one year (2011). The farms submit the same set of bids assumed in scenario 1 (only for 2011). The regulator sets the reservation price of 2011 capacity to $1, and the reservation price for the capacity of all other years to $25. The supplier submits the same set of offers considered for scenario 6. The results for this scenario are given in Tables E.15 and E.16. Some farms, which would have been unable to buy 2011 permits if permits for five years were traded, can now buy some permits[49], for example farms 57 and 47 (Tabled E.13 and E.15). The future capacities, mainly the augmented qunantities offered by the supplier, are not fully allocated (Table E.16), so the farms will be able to buy permits in the next years.

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[49] In scenarios 1 to 6, we considered the same set for bids for the next five years ignoring the effects of interest rates. Hence the results for a five year trading period and a one year trading period are not perfectly comparable.

10.5 Permanent (or Long Term) Loading Rights and Initial Holdings

So far in this work we assumed that the farms hold no initial nitrate loading rights at the time the trading program is launched (or the available rights are invalidated and the farms are expected to buy from the market). As the trading program allows the farms to buy permits for future years, in the consecutive auctions, the farms will possess previously purchased loading permits. We have assumed that the environment and thus the ability of the environment to accept pollution (the receptor capacities) are fully publicly owned. The regulator, acting as a property agent for the public, leases out the receptor capacities to the polluters. Our demonstrations above indicate that the regulator makes a large revenue from sales (results of trading scenarios 3, Table E.9), under the assumption of public property ownership. Even if the reservation prices were reduced, the prices associated with the capacity of early years are set high by farm competition, and the regulator can still make a large revenue.

In most agricultural catchments, the farms have had infinite or long term rights to continue land uses that discharge nitrates. Hence, they implicitly own the dilution capacity of receiving water bodies. For example, most farmers in the United States may be assumed to have infinite rights to discharge the amounts of nitrate they currently discharge, because agricultural discharges are not always regulated (King & Kuch, 2003). In New Zealand, the farmers usually have to obtain consents to release pollutants from the regional environmental authorities. But since the valid period of the consents may be up to 35 years, and can be extended, these consents can also be considered as long term discharge rights. Even though these natural resources are not explicitly privatised on paper, they are implicitly privatised as the individual farms have firm rights to discharge the amount of nitrates they currently do (or sometimes up to a regulated limit). In this case, the receptor capacities are (fully or partially) privately owned. The property owners who lease out receptor capacities are not only the regulators, but also the farms themselves, and hence at least a portion of the revenue from sales should be distributed among the farms, based on their permanent or long- term permit holdings (apart from the payments due for selling previously purchased permits).

Even if the farms are not considered as possessing permanent loading rights, or as sharing ownership of the environment, some initial allocation of permits is required to provide sufficient security to the commercial land users, because the market itself allows them to buy permits up to a fixed number of upcoming years, and there is no guarantee that the farms will be able to buy from the market for the later years. As we mentioned earlier, the proposed market mechanism is not for allocating permanent pollution rights, but for allocating short term leases (Chapter 6). The underlying spatial and temporal complexities and uncertainties involved in nitrate pollution justify such a rental market.

The successful sulphur dioxide trading program in the US can also be considered as a market in property rentals, because the traded sulphur allowances are defined for a single year. But the commercial discharges have some security, because a free initial allocation is made every year based on a formula. Therefore, rather than assuming that the regulator initially possesses all the capacity (constraint) rights traded, some initial distribution of loading rights among the farms would definitely improve the attractiveness of the trading program. Under perfect competition, the initial distribution of permits does not affect the market equilibrium, and thus the final distribution of permits (Coase, 1960; Montgomery, 1972), but it would affect the revenue distribution.

10.5.1 Initial Distribution Based on Prior Land Use

Trading scenario 8: To demonstrate the settlement process under an initial distribution of loading permits, we assume that the 62 hypothetical farms in our demonstration example have permanent loading rights equal to their pre-1998 land use nitrate loading, which has been continued until 2010. So this scenario implicitly considers the available capacities calculated based on sustainable land use (column 4 of Table D.4). Trading takes place for the first time in 2011, and hence the farms do not possess any previously purchased permits. The initial positions will then be determined by the permanent loading rights. For example, if a farm's pre-1998 nitrate loading was 11.9 kg/ha/year, the farm's initial permit position for each of the next five years (S=5) is 11.9 kg/ha/year. The farms can buy or sell, but since the market operates as a gross pool, the offers have to be converted to equivalent bids as discussed in Chapter 6. The farms submit the same set of bids considered for trading scenarios 1 and 3 (assuming that the bids are not affected by the initial positions). This initial distribution does not over-allocate any capacity constraint because both the sustainable receptor capacities and available capacities were calculated based on the same pre-1998 land use distribution; hence the initial distribution should be feasible[50]. We assume that the regulator still owns the unallocated receptor capacities, and offers to sell at the same set of prices considered for scenario 3. No other third parties participate in the market.

Since all the market participants submit the same set of bids considered for scenario 3 and the total available capacities are also the same as for scenario 3, this scenario is equivalent to scenario 3; the only difference is the initial distribution of the receptor capacity rights which does not affect the market equilibrium in capacity rights. Hence the resulting receptor capacity prices, nodal prices, and final permit positions for this scenario are the same as the results produced by scenario 3 (Tables E.7 and E.8, and the first two columns of Table E.9).

The calculated net payments due from (to) the farms are given in Table E.17 (a negative value indicates that the farm makes a net revenue from the market by selling permits). The regulator's (updated) starting capacity positions, final capacity positions, and the payments due to the regulator for selling each year's capacity are also given in Table E.17. Effectively, some farms are selling and some are buying. Hence the regulator gets only 25% of the revenue it would have gained under full capacity ownership ($5,452 thousand, compared to $21,877 thousand under full capacity ownership). The prior land use based initial allocation of permits results in 75% of the total revenue being distributed among the farms.

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[50] However, we had to set the initial positions to 97% of the simulated pre-1998 land use nitrate loading because setting the initial positions exactly equal to pre-1998 loading created a few violations in the capacity constraints. This problem was caused by rounding errors and unit conversion errors in the response coefficients and available capacities obtained from physical simulations (for example, the response coefficients of some farms add up to 1.01).

10.5.2 Problem of Setting Initial Positions

Initial distribution based on prior land use (regardless of whether the farms are considered as the owners of the receptor capacity or not) is not always feasible. In this case, the market authorities have to derive some mechanism to reduce the initial rights. As discussed earlier, any initial distribution of loading rights may not bind all the capacity constraints, and the regulator may still make money from the market. On the other hand, when the market participants know that they will be deemed to have some initial position based on current or previous land use nitrate loading, they could be motivated to behave strategically. Literature on market power and strategic behaviours in permit markets suggest that the initial distribution of permits is the major factor which determines the market power in permit markets (Egteren & Weber, 1999).

One way to solve the problem of initial distribution is creating another independent market in long term or permanent pollution rights. This method has been successfully adopted by the Hunter River Salinity Trading Schema. Under this system, point sources trade salt discharge rights on a daily basis, relative to long-term (10 year) salt discharge rights purchased from another independent auction. The discharge rights are defined proportionally (rather than quantitatively) as a share of the total allowed salt load into the river. Similarly, under tradable fishing quota systems, markets in quota leases exist together with markets in permanent fishing rights or quotas (Newell, et al., 2005; Newell, et al., 2002).

However, when the nonpoint sources and the dispersed and delayed nature of nitrate pollution are concerned, defining permanent pollution rights is difficult. In both of the above examples, the permanent and thus the lease rights are defined proportionally as quotas so that they are adjustable according to availability. Hence, permanent rights may be defined as shares of receptor capacity or shares of receptor capacity in each year (as a perishable commodity). Another market-based approach for setting the initial positions is to create an independent market in “hedge contracts” similar to the hedge contracts exercised outside centralized power markets to protect against price volatility (Ring 1995).

The purpose of the preceding discussion was to highlight the importance of having initial allocations, and to provide some ideas about setting the initial positions. However, there is no globally optimum allocation of initial rights, the best criterion for a given catchment will depend on “what the community think is fair and what will be politically feasible” (Kerr & Lock, 2009).

Chapter 11

11 Point and Nonpoint Source Trading

11.1 Introduction

This chapter blends two important considerations for a market-based mechanism designed to control water pollution from nitrates. First, we present a way to extend the scope of the market to include point sources. We discuss the extent to which the point and nonpoint sources can interact in the market, and the factors that restrict their interaction.

Second, we study the extent to which the nonpoint sources themselves can interact in the market. We show how the competitiveness in permit markets can be naturally restricted by the catchment hydro-geology. We derive some measures that describe the ability of the nonpoint sources to trade with each other. The major purpose is to identify the essential and desirable conditions for proper functioning of a market in nitrate loading permits. We also study what the market designers could do to increase the opportunities of the sources to actively participate in the market.

11.2 Including Point Sources[51]

Since nitrates enter waterways from both point and nonpoint sources, including the point sources in the trading program is important. The trading system we have

[51] This section is based on Prabodanie et al. (2009).

discussed so far is implicitly capable of including the point sources. The only difference is that while the nonpoint sources trade loading permits the point sources trade “emission” permits. Emission permits specify the maximum allowed nitrate emission into a *receptor* (possibly into a river or a lake) during a specified time period (year), while the loading permits specify the maximum allowed nitrate loading into *the groundwater system* underlying a farm.

Since point source emissions are immediately received by some receptor r^0, 1 kg nitrate emission from any point source i in any year would increase the nitrate mass in receptor r^0 by 1 kg in the same year. Hence, the response coefficient $H_{ird} = 1$ for $r = r^0$ and $d = 0$, and $H_{ird} = 0$ for all other r and d.

The response coefficients used in this work are not intended to describe nitrate transport in surface water, but in groundwater. Hence even if nitrate could reside in receptor r^0 for more than a year, or could flow down to another connected receptor, we still assign $H_{ird} = 0$ for all $r \neq r^0$ and $d \neq 0$, to produce emission permit prices and allocations which are comparable with loading permit prices and allocations. However, the inter-receptoral or inter-temporal relationships caused by nitrate residence and transport in surface water are described by the multi-receptor and multi-period constraints discussed in Chapter 7.

The trading system proposed in Chapter 6 does not require any major extension to include point sources. Point sources can decide on the size of the permit required for each year in kg/year from the quantity and nitrate concentration of the effluents they wish to discharge into their receptors during the year. They can submit a set of bids for each permit year as the farms do.

In a competitive market, point sources would bid based on the cost of reducing nitrate emissions (marginal abatement costs). Since point sources have the option of in-plant or outside treatment of effluents to reduce nitrate, the abatement costs will be affected by the treatment costs as well as the cost of downscaling operations. A rational municipal or industrial point source, given that she cannot affect the price charged for nitrate emission, would choose either to buy a permit or to treat effluents (assuming treatment is more economical than downscaling), whichever is cheaper, and hence bid to buy permits based on her marginal cost of treatment.

The same Optimal Resource Allocation Model (ORAM) presented in Chapter 8 can facilitate simultaneous trade in loading and emission permits, redefining f as a (point or nonpoint) source rather than a farm, and having all point sources located on each single receptor grouped into a single distinct node.

The nodal price, $\beta_{ns} = \sum_r \sum_{t=s}^{s+T} H_{nr(t-s)} \gamma_{rt} + \sum_i A_{nsi} \pi_i$.

Since point sources do not affect the constraints on loading, if node n represents point sources then $\beta_{ns} = \sum_r \sum_{t=s}^{s+T} H_{nr(t-s)} \gamma_{rt}$.

If node n represents the point sources discharging into receptor r^0:

$$\beta_{ns} = \gamma_{r^0 s} = \lambda_{r^0 s} + \sum_j B_{r^0 sj} \delta_j .$$

In the absence of any multi-receptor/period constraints, the point source (emission) price equals the capacity price of the receiving water body. In this case, the point source price for any year is independent of the prices associated with other years as well as other receptors. If the receptors are connected and/or nitrate resides in a receptor for more than a year, the second component of the point source price can be non-zero, and hence the effects of nitrate residence and transport in surface water are reflected by the point source prices.

For example, in the hypothetical catchment example presented in Chapter 8, the point sources that discharge into the lake directly will have to pay $\varepsilon_s = \lambda_{1s} + G\delta_s$ per kg nitrate emission into the lake in year s. Effectively, for discharging nitrate into the lake in any year, the point sources have to pay the associated receptor capacity price (λ_{1t}) plus the expected cost of carrying forward ($G\delta_t$) to the next year. Those who discharge nitrate directly into a stream will have to pay the associated capacity price of the stream plus the lake price adjusted by the proportion of in-stream nitrate carried down to the lake ($\gamma_{rt} = E_r\varepsilon_t + \lambda_{rt}$). Thus the upstream emission prices reflect the effects of the upstream receptors on the downstream receptors.

11.2.1 Point-Nonpoint Source Trading Demonstration

To demonstrate the effects of having point sources based on our demonstration example (Appendix D), we consider a hypothetical point source located beside the river which is the only receptor considered. Since we have only one receptor, and the point sources located on the same receptor are considered as hydro-geologically identical (having similar effects on the market constraints which determine the prices), we consider only one point source (which may be a group of point sources). Since the model includes only receptor capacity constraints, and no other market constraints, the point source emission price for any year is equal to the receptor capacity price of that year (λ_{1s}).

Trading scenario 9: This scenario assumes that the point source (PS) submits five bids as given in Table 11.1 for each of the five years from 2011 to 2015 (S = 5) ignoring the effects of discounting.

Bid	Quantity(kg/year)	Price ($/kg) for scenario 9	Price ($/kg) for scenario 10
1	5000	$5.00	$50.00
2	5000	$4.00	$40.00
3	5000	$3.00	$30.00
4	5000	$2.00	$20.00
5	5000	$1.00	$10.00

Table 11.1: Point source (PS) bids.

Available receptor capacities are based on sustainable land use (column 4 of Table D.4). The farms and the regulator submit the same sets of bids and offers considered for trading scenario 3.

The results produced by the ORAM for this scenario are given in Tables E.18 and E.19 of Appendix E. The resulting allocations to point and nonpoint sources (Table E.18) clearly indicate that the nonpoint sources dominate the market. The farms get the same allocations as per scenario 3 (Table E.7) which did not include the point source. The PS buys only the remaining 2011 capacity after allocation to the farms, and does not affect the farms at all. The PS cannot buy any permits for the years 2012 to 2015. The reason is that the PS price per kg nitrate emission into the river in any year is equal to the associated receptor capacity price (Table E.19) which is well above the PS's highest bid of $5.

However, when a farm loads a kg of nitrate into the aquifer, only a small fraction goes into the stream in any one year. Hence they are able to buy receptor capacity even though the capacity price is higher relative to their bids. For example, the highest response coefficient for $d = 0$ is 0.404, and only 12 farms out of 62 have $H_{frd} > 0.01$ for $d = 0$, which means that all other farms have to pay less than 1% of the capacity price per each kg of permit purchased, while the PS has to pay 100% of the capacity price for each kg purchased. Hence, the point sources will not be able to buy unless they are prepared to pay the price for instant effects.

The point and nonpoint source abatement costs, or more closely, the cost of reducing land use nitrate loading and the cost of point source effluent treatment are the major factors which determine the competition between the two types of sources and the extent to which they interact in the market. Since we do not have accurate information about either point source abatement costs or farm profit functions, we do not study the issue any further. To study how the underlying physical systems affect the interaction between point and nonpoint sources, we assume that the PS is prepared to pay a higher price for permits, possibly because the abatement cost is high.

Trading scenario 10: This scenario assumes that the PS increases all bid prices tenfold (3rd column of Table 11.1), so that her bids lie in a competitive range compared to the receptor capacity prices produced by scenario 9 (Table E.19). This is the only difference between scenarios 9 and 10. For this scenario, the outcomes of trade, the prices and allocations, are given in Tables E.20 and E.21. The PS can now buy a relatively large permit for each year, and the PS purchases affect many nonpoint sources. In Table E.20, the reduced nonpoint source allocations (compared to the results for scenarios 3 and 9) are highlighted. The farms (15, 16, 23, 27, 33, 37, 40, 41, 45, 47 to 49, and 51 to 62) whose final permit positions were reduced to meet the point source demand, are those which have shorter delay times. By paying more, the PS can purchase permits which would otherwise have been purchased by the nonpoint sources. The receptor capacity prices associated with the first five years are pushed up by the competition between the point and nonpoint sources (Table 21). These results provide evidence that there is significant trading interaction in year-1 to year-5 permits between point and nonpoint sources.

Trading Scenario 11: To study how the interaction between the point and nonpoint sources is affected by the number of trading periods, this scenario assumes that the number of trading years S was reduced to one (S=1) and permits are traded for the upcoming year only. The regulator submits the same set of bids considered for scenario 3. The farms also submit the same set of bids considered for scenario 3 (for year 2011 only). The resulting final allocations for this scenario, without and with the PS participating in the market (submitting the set of bids in the 3rd column of Table 11.1), are given in Table E.22. The results indicate that nonpoint source allocations are not much affected by the PS participation in the market. The final permit positions of only a few farms (16, 41, 61, and 62) are reduced by a small amount (in terms of kg/ha/year). These results provide evidence that there is some trading in year-1 permits between point and nonpoint sources, but not much.

Scenario 12: This scenario considers permit trading for 10 years (S=10). It also assumes that the regulator submits the same set of bids considered for scenario 3, and the farms also submit the same set of bids considered for scenario 3 (for 10 years) ignoring the effects of discounting. Based on this scenario, we compared the resulting final allocations without and with the PS participating in the market (submitting the same set of bids in the 3rd column of Table 11.1 for each year). The results indicate that the allocations to even more farms are reduced by the PS participation in the market (farms 14, 26, 31, 35, 38, and 43; and the 24 farms affected under scenario 10).

When the point sources bid to buy future permits, nonpoint sources are burdened with their bids for recent permits (for example, year-1 permits) competing with the point source bids for future permits (for example, year 5-permits) because recent nonpoint source permits and future point source permits affect the same constraints. Hence, the interaction between point and nonpoint sources generally increases when the number of trading periods (*S*) is increased. However, beyond a certain point, increasing the trading period *S* further does not significantly increase the interaction (when $S = 1$, only four farms were affected by PS participation in the market; when $S = 5$, another twenty farms were affected, but when $S = 10$, only six other farms were affected).

11.2.2 Discussion: Point Nonpoint Source Trading

The trading interaction between point and nonpoint sources, and thus the usefulness of point and nonpoint source trading, is mainly determined by the abatement costs of the two types of sources, more specifically, the cost of shifting to less nitrate intensive farming, and the cost of effluent treatment (assuming that that the participants bid based on their true economic values). Generally, point source bids for any particular year will compete with the nonpoint source bids for several years adjusted by the relevant response coefficients (due to the dispersed and protracted effects of nonpoint sources). Hence, the point sources may have to pay more to out-compete the nonpoint sources. Without reliable information on the cost functions, we cannot predict how far the two types of sources can interact in the market.

To study the physical limitations for trade between the two types of sources, we assumed that the abatement costs of point and nonpoint sources are such that their bids lie in a competitive range. According to our results, the extent to which trade occurs among the two types of sources depends on the properties of nonpoint sources, mainly the time lags associated with nonpoint sources. The faster the diffuse loads reach their destination, the greater the opportunities for trade between point and nonpoint sources. However, a market which trades permits for a single upcoming year provides fewer opportunities for trade between point and nonpoint sources, because NPS permits have effects on many future years while PS permits have effects on a single immediate year. Hence, two markets are likely to exist, unless the nonpoint sources have significant impacts in the same year of the loading. When permits for multiple years are traded simultaneously, nonpoint source bids for recent years will compete with the point source bids for future years, and the market prices are pushed up by intensive competition.

Provided that the abatement costs are competitive, point and nonpoint source nitrate trading appears to be most suitable when nitrate transport in groundwater is sufficiently fast and/or point sources are willing to buy future permits. The market designers can select the optimal number of years for which the permits are traded (S) based on the nonpoint source delay times to increase the trading opportunities between point and nonpoint sources. Uncertainties in the physical system and existing environmental regulations may restrict the ability to increase S, but the ability to buy permits for many years will provide more security to the commercial sources. For example, if the delay times associated with all the nonpoint sources are greater than five years, setting $S \leq 5$ would provide no opportunities for point and nonpoint source trading; unless S is set higher, two markets would operate independently.

11.3 Market Competitiveness[52]

Market competitiveness usually describes the rivalry among the firms. Research into market power and strategic behaviours in general environmental permit markets suggests that those issues are mainly related to the initial distribution of pollution rights (Egteren & Weber, 1999).

A market participant who is financially stronger than others can have market power, the ability to raise the prices and buy more or to monopolise the market. Auction markets can be more susceptible to such gaming behaviours (Stoft, 1999). In electricity markets, game theory models have been used to estimate potential efficiency losses from a Nash equilibrium due to the strategic behaviours of powerful suppliers (Migliavacca, 2007; Saguan, Keseric, Dessante, & Glachant, 2006; Stoft, 1999). A Nash equilibrium is obtained by solving a competitive market equilibrium model, but this requires information on the cost functions of the players (Migliavacca, 2007; Saguan, et al., 2006). A game theoretical approach is then used to estimate how

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[52] This section is based on Prabodanie and Raffensperger (2009a).

much the social welfare would change if the players game the bids above or below the true economic values with strategic intents.

In the context of nitrate permit markets, if information is available on the profit functions of the farms, similar approaches may be used to estimate how far the prices can be distorted. However, it is difficult to predict what strategies the market participants would play in the real world. Without such information about the players or any real data collected from active permit markets, results of game theoretic analysis may not provide an accurate picture of the market competitiveness.

The competiveness in nitrate permit markets may be limited by factors other than market power. As discussed earlier, loading permits are different compositions of receptor capacities (and other services), they are not directly comparable between farms, and non-comparable permits provide fewer opportunities for trade. Even if the players were ideal competitors and did not behave strategically or exercise market power, the ability and willingness of the farms to trade future capacities in the market are limited by the catchment hydro-geology, which determines the composition of each farm's loading permit. Therefore, the competitiveness in these permit markets is determined by two types of factors: (1) participant characteristics (capabilities, strategic intents, current permit holdings) and (2) catchment hydro-geology.

This section looks at the extent of competition determined by the catchment hydro-geology which is beyond the control of market designers and the players. We ignore both the resource banks (including the regulator) and the point sources, to study how far the nonpoint sources themselves can trade with each other. We assume only the receptor capacity constraints and no other market constraints. In this section, we use the term "market competitiveness" to refer to the extent to which the farms can participate in the market and trade with each other, given that the only factor which restricts their ability to inteact with each other is the catchment hydro-geology, not the individual economic characteristics and capabilities.

In the following discussion, we assume a single receptor situation ($r = R = 1$), but the models and measures are applicable to cases where $R > 1$ with minor changes. We consider two cases: (1) farms can trade only year-1 permits ($S = 1$) and (2) farms can simultaneously trade permits for several years ($S > 1$). In the former case, if a farm $i \in [1, 2, \dots, F]$ has $H_{iRd} > 0$ for all $d \leq 4$, and $H_{iRd} = 0$ for all $d > 4$, while all other farms have $H_{iRd} = 0$ for all $d \leq 4$, then farm i is hydro-geologically isolated, and cannot trade with others, because it does not compete for the same commodities (capacities of the same years) as others. However, if the farms can simultaneously trade year-1 to year-3 permits, farm i will compete with other farms for some constraints (the capacities of years 5 and 6). Following this general understanding, we derive numerical indicators of competitiveness in the next sections.

11.3.1 The Herfindahl-Hirschman Index (HHI)

The Herfindahl-Hirschman Index (HHI) is a measure of buyer/seller concentration and an indicator of competition among the buyers/sellers (Liston-Heyes & Pilkington, 2004). HHI is calculated from the sum of squared market shares of firms purchasing (selling) a particular product. Clearly, HHI is expressed relative to a single commodity.

To assemble a unit year-1 loading permit, farm i has to buy $H_{iR(t-1)}$ of the capacity of each year t. The farm's consumption rate of year-t capacity is given by the response coefficient $H_{iR(t-1)}$. Hence, farm competition for year t capacity is determined by the distribution of $H_{fR(t-1)}$ over f, in the $(t-1)^{\text{th}}$ row of the response matrix for receptor R. We may define a farm's relative consumption rate of year-t capacity, RCR_{iRt}, as a share of the cumulative consumption rate of all the farms.

$$RCR_{iRt} = H_{iR(t-1)} \;/\; \textstyle\sum_f H_{fR(t-1)} \qquad \text{(C-1)}$$

Considering the relative consumption rate of each farm as a natural market share, we may now define a modified HHI, HHI^M for a market in year-t capacity of receptor R (a single commodity), as the sum of squared relative consumption rates of the farms.

$$HHI^M{}_{Rt} = \textstyle\sum_f (RCR_{iRt})^2. \qquad \text{(C-2)}$$

Similarly, we can define the $HHI^M{}_{rt}$ for each receptor r and time period t. The modified index $HHI^M{}_{rt}$ indicates the extent to which the farms could compete for the capacity of year-t of receptor r. For a demonstration, we calculated the values of $HHI^M{}_{rt}$ for our demonstration example presented in Appendix D, using the response matrix coefficients of the single receptor and the 62 hypothetical farms given in Table D.3. Assuming a market to allocate loading permits for year 2011 (S = 1), the estimated values of $HHI^{M}{}_{1t}$ for the capacity of each year from 2011 to 2050 (for each t=2011+d) is given in Table E.23.

The values of $HHI^{M}{}_{Rt}$ for t = 2012, . . ., 2035 are below 0.1. An HHI of 0.1 or below is usually considered as a competitive market (Ruster & Neumann, 2006). Therefore, the results indicate that the market is competitive for the receptor capacity of some years (24 years from 2012, . . ., 2035), but for the capacity of some years, (for example t=2060 and t=2059), the market is currently dominated by a few players. However, the farms cannot buy the capacity of tail years without buying capacity from the other competitive markets, because they can trade only loading permits. Hence, even if the competition for a few capacity constraints is significant relative to the number of farms in the catchment, the combined market would probably function actively.

The index derived above gives an approximate idea about the buyer concentration for each commodity traded in the combined market. However it does not give a clear picture of overall market competitiveness. Therefore, we derive a new measure called the "Contiguity Index" which measures the contiguity of locational (farm) loading permits to provide an overall picture of the extent to which the farms can trade with each other, and thus the overall market competitiveness.

11.3.2 Contiguity Index (CI)

Assuming S = 1, we first define a contiguity index for a pair of farms i and j, to measure the extent to which they can interact in the market.

Define $CI_{(i,j)} = \frac{1}{T`}\sum_{t=1}^{T`}(H_{iRt} \times H_{jRt})^{|H_{iRt}-H_{jRt}|}$,

where $T`$ is the number of years for which (at last one of) $H_{iRt} > 0$ or $H_{jRt} > 0$.

If either $H_{iRt} = 0$ or $H_{jRt} = 0$ for all t (if the columns corresponding to i and j in the transport coefficient matrix of receptor R are not overlapping) $CI_{(i,j)} = 0$, and the pair of farms cannot trade at all. If $H_{iRt} = H_{jRt}$ for all t (if the columns corresponding to i and j in the transport coefficient matrix coincide perfectly), $CI_{(i,j)} = 1$, the pair of farms can trade perfectly. Since $H_{frt} \leq 1$ for any combination of f, r, and t, when the difference between H_{iRt} and H_{jRt} ($|H_{iRt}-H_{jRt}|$) increases, $CI_{(i,j)}$ tends to zero. When the difference between H_{iRt} and H_{jRt} decreases, $CI_{(i,j)}$ tends to one. $CI_{(i,j)}$ can take a value within the range [0,1]. It indicates the extent to which the pair of farms can interact in the market, and a greater the value of $CI_{(i,j)}$ is always preferable for a market.

From F farms in the market, we can extract ${}^{F}C_2 = (F-1)F/2$ distinct pairs. Therefore, the overall catchment contiguity can be given by:

$$CI = \frac{2}{(F-1)F} \sum_{(i,j)} \frac{1}{T'(i,j)} \sum_{t=1}^{T'(i,j)} (H_{iRt} \times H_{jRt})^{|H_{iRt}-H_{jRt}|}.$$

Large agricultural catchments can have a large number of farms with widely different spatial and temporal effects. Even if the farms cannot interact with everyone else in the market, if they can interact with a sufficiently large number of farms, the market would still be sufficiently competitive. However, the value of the index CI will be smaller if each farm had similar effects with a smaller number of farms compared to the total number of farms. For example, if there were 100 farms, each farm having relatively higher pair-wise index values with about 10 farms and relatively lower index values with others, the overall catchment contiguity index can still be small. However, by looking at the distribution of the pair-wise index values, and by calculating the overall contiguity indices for close subsets of farms (for example, we may calculate the overall index for sets of 10 adjacent farms, rather than for all the farms in the catchment), the market designers can understand how far the nonpoint sources can interact with each other, and the degree of market segmentation also. The proposed index may not be a perfect indicator of the overall opportunities for multilateral trading in the catchment, but it provides an idea of the extent to which the farms can trade with each other. Further study is required to better interpret the proposed index.

For demonstration, we calculated the pair-wise and overall values of CI considering the 62 hypothetical farms in our demonstration example discussed in Appendix D. The results are given in Table E.24 of Appendix E (only some of the calculated values are given). The farm pairs having nearly coinciding response coefficients, 46 and 50, 35 and 53, and 17 and 19 have the highest values 0.99, 0.97, and 0.95 respectively. Even though the overall index for the 62 farms is only 0.33, the overall values for sets of 10 farms are around 0.5 or higher. Hence, for our example, the market in nonpoint source loading permits would be sufficiently competitive, even if permits are traded for the upcoming year only ($S = 1$).

11.3.3 Multiple Year Permit Markets

When $S>1$, farms can trade permits for several years simultaneously. Earlier in this chapter, we discussed that multiple year permit markets provide more opportunities for trade between point and nonpoint sources compared to single year permit markets. Therefore it is interesting to study how the competition among the nonpoint sources themselves would be affected when permits for multiple consecutive years are traded simultaneously.

Assuming that the farms would trade the same quantities of year-1 to year-S permits, we may define a cumulative transport coefficient, H^S_{fRd}, to measure the cumulative effect of a unit (1 kg/year), permit continuously valid from year-1 to year-S.

$$H^S{}_{fRd} = \sum_{s=1}^{\min(S,d+1)} H_{fR(d+1-s)}$$

We can then calculate HHI^M_{Rt} for the case of $S>1$, by replacing H_{fRd} with H^S_{iJd} in the formulation given above. To calculate CI for this case, we have to replace H_{fRd} with $H^S_{fRd}/\min(S,d+1)$ in the formulation of CI to get H^S_{fRd} in the range of 0 and 1. For our example (Appendix D), the calculated contiguity index for $S=5$ is 0.39. This is higher than the value for the year-1 permit market, but for sets of 10 and 20 farms, the index values significantly increase when S is increased to five (Table E.24). The extent of nonpoint source competition increases when the number of trading periods increases. This result is consistent with the previous observations on point and nonpoint source competition which also increases with S.

11.3.4 Discussion

In agricultural discharge permit markets, the competitiveness driven by individual farm characteristics and the structure of the market is manageable. Therefore, the competitiveness driven by hydro-geology is worth studying before a market is implemented.

In this section, we proposed some measures to evaluate the competitiveness of a market in nitrate discharge permits. We studied the competitiveness driven by hydro-geology, which is beyond the control of both the market participants and the designers. Our results suggest that the extent to which the farms can participate in the market depends on the extent to which their transport coefficient matrices overlap. If the farms are hydro-geologically isolated, tradable permits do little favour to the farms. However, if the trading system allows them to buy permits for several future years, the farms would be able to trade with each other in a competitive market. Further research on applying the proposed measures would help market designers understand the nature of competition better.

Chapter 12

12 EXTENSIONS, APPLICATIONS AND CONCLUSIONS

12.1 Introduction

This chapter presents possible extensions and applications of the proposed market mechanism, and closes the thesis with our conclusions and directions for further research.

We discuss the physical and behavioural aspects of the problem we have not explicitly included in the market models, but can be included: nitrate runoff, compliance-related penalties and rewards, and integer constraints. We briefly describe how to extend the models to include those features. Then we discuss the applicability of the models and concepts to other water pollution problems and other environmental problems.

In conclusion, we summarize the strengths and the limitations of the proposed market mechanism. We discuss the factors beyond our control which can lead to market failures, mainly the non-convexities and uncertainties in the underlying physical system. The chapter closes with some directions for future research.

12.2 Extensions

12.2.1 Runoff

In Chapter 1, we mentioned that nitrate loss from agricultural land occurs mainly due to leaching, but runoff losses are also possible depending on the soil topography, and location of the farms. Since the pollutants carried off by surface runoff and soil erosion reach a surface water body quickly, and do not usually migrate to groundwater, the effects of runoff are similar to the effects of point source emissions. Hence, the simplest way to account for the effects of runoff is requiring the nonpoint sources (from which nitrate may be lost due to runoff, for example, the farms beside a river) to hold an emission permit to match the expected annual runoff, in addition to the loading permits.

12.2.2 Integer Constraints

As discussed in Chapters 7 and 9, discontinuities in the land use profit functions can create non-convexities in permit markets, requiring integer constraints to model the non-convexities. Minimum permit requirements and non-divisible quantities (bids) are the common causes of such non-convexities. Market clearing models require integer variables to model these constraints. A market-based mechanism may not be acceptable to commercial land users unless these requirements are met.

Electricity markets which are based on LP models do also have similar non-convexities, for example, start-up and shut-down costs of the generators. Several different methods have been proposed to find optimal prices under non-convexities arising from integer variables. O'Neill, Sotkiewicz, Hobbs, Rothkopf, & Stewart (2002) proposed to solve an integer programming problem first, replace the integer constraints with equalities that force the integer variables to their optimal values, and then solve the resulting LP to find the market clearing prices. A few other methods have been proposed in Ring (1995) and Bjørndal & Jörnsten (2008). Any of those methods may be used to handle the non-convexities that arise from integer constraints such as minimum permit requirements.

12.2.3 Compliance Related Penalties and Rewards

Unless the permit users comply with the permitted discharge levels, the main purpose of tradable permits, achieving environmental goals at minimum cost, will not be achieved. Therefore, continuous monitoring is required to realise the expected benefits. Continuous compliance monitoring through automated devices is one of the factors contributing to the success of the SO_2 emissions trading program (Schary & Fisher-Vanden, 2004). Unlike the effects of releasing gases, the effects of diffuse discharges do not appear instantly, and hence the environmental authorities may have to carry out compliance monitoring relative to the permitted activities, and take actions to prevent irreversible violations. Together with continuous monitoring, violation penalties are required to ensure proper behaviour.

Compliance-related penalties and rewards also improve the attractiveness of permit trading programs (David, 2003; Schary & Fisher-Vanden, 2004). The SO_2 emissions trading system penalises users who violate permitted emission levels by requiring them to buy a permit to cover the previous year's deficit in the immediate next year and to pay an administrative penalty. Those who perform well below the permitted emission level are rewarded by the ability of banking (the ability to carry forward the unused allowances).

A similar mechanism can be incorporated into the proposed trading program for nitrate permits to encourage better performance and to discourage violations. Since the effect of nitrate loading in one year is different from the effects of loading in another year, loading permits cannot be carried forward, or be surrendered to compensate for previous violations. We suggest that this problem can be handled by including the previous year (year-0) in the market clearing models, and requiring the non-compliant farms to buy year-0 permits to match the previous year's deficit, and allow the over-compliant farms to sell unused year-0 permits. This method allows farms to sell unused permits and to pay for over-use in the immediate next year, because including many previous years in the market model can create confusion and provide space for strategic behaviours.

If the last year's actual loading levels are known (by the farms, the regulator, and the market operator) at the time trading takes place (the beginning of every year), the available (tradable) capacities can be re-set accordingly ($C`_{rt}$). In the market-clearing LP models, equality constraints can be included to force those who violated the permitted loading level to buy a year-0 permit to match the violation (q_{f0} = violation), and to allow those who performed better to sell the unused permit (q_{f0} = 0). If the violations are high, the available capacity can be negative, meaning that some remediation activity is required. In that case, the market requires an offer of augmented capacity to cover the violation. If the regulator sets a bid for each capacity constraint (assuming that the regulator bids to buy if the available capacity is zero), the violators will be buying from either the farms or the regulator, and the better-performers will be selling to either the farms or the regulator. If the equality constraints are binding, the violated farms may have to pay a higher price for year-0 compared to their bid prices, and the better-performers may have to sell at a price below their reservation.

12.3 Applications

The problem addressed in this thesis, allocation of nitrate discharge permits among different types of sources, is a common pool, multilateral trading problem with complex interactions and a large number of interdependent and interrelated constraints. The basic idea is modelling the optimal allocation as a mathematical program, possibly as an LP, from which the equilibrium prices may be obtained straight off. Thus the proposed concepts and the models are generally applicable for other environmental pollution problems with complex interactions, where it is difficult to define a common standardised commodity capable of achieving environmental quality and sustainability requirements, for example, allocation of fishing rights, land development rights, and other environmental pollution rights (noise, air pollutants, and other water pollutants). If the demand for those rights and the physical interactions in the system can be modelled with sufficient accuracy, and the modelled constraints form a convex feasible region for allocations, the proposed market mechanism can be used to price those environmental resources efficiently relative to submitted bids or value functions.

Since we specifically addressed nonpoint source water pollution, the closest applications are other nonpoint source pollutants such as phosphorus and sediment. However, unlike nitrogen, phosphorus does not leach but remains in the soil. Phosphorus loss from agriculture occurs due to soil erosion and surface and sub-surface runoff. Sediment also reaches the waterways via surface runoff and soil erosion. The travel times (time to travel from land to water bodies) of those pollutants are shorter, because the medium is fast-moving runoff or erosion, but some amount can be lost during transport. The proposed market mechanism can be used for phosphorus and sediment with shorter planning horizons, but response coefficients should be defined and estimated in different ways. The underlying important assumption in using the response matrix technique is that the relationship between pollutant loss from farms and effects at the receptors is linear, but this assumption is less likely to hold for phosphorus and sediment, because the transport medium is surface runoff and soil erosion which are not as stable as groundwater flow systems. On the other hand, the source-receptor relationships can be affected by the intensity rain-fall. Therefore, simplified delivery factors rather than response coefficients (for example, proportional attenuation factors for each farm) or ex-post market clearing (Ring 1995) based on observed pollutant loads may be considered for these pollutants.

12.4 Conclusions

The core of this thesis was a new market-based mechanism for allocating nitrate discharge permits among point and nonpoint sources. The proposed market operates as a centralized auction. The pollution sources submit a set of bids to the auction, indicating the benefit gained from each unit of loading permit allocated. Environmental agents submit offers to lease out the capacity of water bodies to accept nitrates. The auction operator runs a linear program which maximises the benefits from trade (as indicated in the bids and offers), subject to a set of constraints which describe the underlying nitrate transport system, the ability of water bodies to accept nitrates, and operational constraints of the sources. The LP solution provides the optimal prices and allocations which clear the market. The operator then settles the market ex-ante by informing the cleared permit positions of each source, collecting money from buyers, and paying the sellers.

12.4.1 Strengths

Management of diffuse water pollution sources requires an integration of physical and economic models. Despite the growing interest towards market-based mechanisms, the research to date has failed to incorporate accurate representations of the physical systems into the market designs. The major strength of our approach is the ability to incorporate the underlying physical system into the market clearing models, while maintaining the simplicity of the program and low transaction costs. Our approach allows the diffuse sources to buy a single permit for each year, ensuring that any large set of (relevant) environmental and commercial constraints are met over a period of any appropriate length.

The proposed system efficiently handles the common causes of market failures such as transaction costs and externalities. First, users buy from and sell to a centralized auction once every year, so they do not have to find trading partners and negotiate contracts. Second, the users are not required to validate trades or get approvals. Hence transaction costs will be negligible.

All the externalities of trade are internalised into the market, because the market can charge the polluters based on prices associated with any number of constraints which describe the effects of discharges. The authorities will have the flexibility to adjust the maximum allowed levels of pollution, to add more constraints, or to set time horizons through which the target quality levels are to be achieved. Users can be given more flexibility by letting them specify conditions such as minimum permit requirements. Therefore, we argue that, as the US SO_2 emission trading program, the proposed trading system would provide *sufficient* security and flexibility to both the environmental authorities and commercial polluters.

We showed that creating a "free" market to trade nitrate permits, especially for nonpoint source nitrate loading permits, is almost impossible. The system we proposed is not a free market, but it can allocate permits efficiently taking into account the underlying pollutant transport system more accurately.

12.4.2 Limitations

The proposed trading program would be most suitable when the underlying solute transport system is approximately convex and deterministic. Non-convexities and uncertainties in the physical system (as well as economic conditions) can result in failures.

We used the response matrix technique assuming that loading permit allocations (mass nitrate loading) and groundwater recharge rates (via water percolation from soil) are separable, which they are not. Loading permits and thus the land use intensity can affect the recharge rates. For example, groundwater recharge from a dairy farm is usually greater than recharge from dry stock, sheep and beef.

Even if recharge rates increase with land use intensity, and thus nitrate loading, the response coefficient for a given delay may increase or decrease with recharge, what could be guaranteed is that the response profile (the series of response coefficients over time) would change. This is a completely non-convex situation which cannot be handled by a piece-wise linearization.

All the physical parameters used in the models, mainly the response coefficients and the available capacities, are estimated values. Therefore, uncertainty cannot be avoided. However, since the time horizon can be longer, and values of those parameters cannot be estimated with 100% accuracy at any point in time, multi-stage stochastic programming approaches may not always help. Given the political, economic, and climatic uncertainties, valuation of future capacities cannot be real, and therefore, the reluctance to commit present economic benefits for an uncertain future may challenge the feasibility of any market mechanism proposed for nitrate.

If the uncertain parameter values can be estimated with associated probabilities, a chance constraint approach may be developed to meet the environmental constraints with given probabilities. However, chance constraints can create non-convexities in pricing models.

12.5 Directions for Future Research

Even with assimilative pollutants, the ability of the water systems to accept pollution is limited, and therefore, the assimilative capacity is a scarce resource. Our contribution was only for allocating the available capacity efficiently. Research into increasing capacity supply through in-situ and ex-situ treatment, wetlands, and other means, as well as decreasing the demand for capacity through best farm management practices are of the utmost importance.

We presented a generally applicable market design and LP models, but a given catchment can have unique physical and economic conditions. Therefore, the feasibility of a trading system will be determined by capacity availability, differences in the physical and economic properties of the sources (response coefficients and abatement costs), how frequently the groundwater flow system changes, and how far we can rely on the estimated physical parameters. These questions are worth studying at the catchment scale. Trading in a given catchment may be simplified and improved by finding a best compromise planning horizon T and optimal S (the number of periods for which permits are traded).

Models for evaluation of receptor capacities and participant-side optimisation remain to be studied. Further research into other applications discussed above is highly recommended.

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Appendix A

GROUNDWATER SOLUTE TRANSPORT EQUATION

This appendix provides a brief description of the general groundwater solute transport equation used to model nitrate transport in groundwater. Most groundwater quality management models, as well as ours, are based on a black box approach to incorporate the underlying physical system, and do not include explicit representations of the solute transport equations. The purpose of this appendix is to open the black box, providing some insight into what actually happens once nitrate leaches into groundwater aquifers.

According to the principles of contaminant transport modelling[53], the transport of contaminants as solutes in groundwater occurs due to three main processes: advection, dispersion, and chemical reaction.

A.1 Advection

Advection refers to the movement of solute particles with groundwater at the same velocity of groundwater flow. In many contaminant transport problems, advection is the dominant cause of transport. The mass balance equation which governs pure advective transport of a contaminant in a porous medium is:

[53] Sources: Zheng and Bennett (2002) and Zheng and Wang (1999)

$$\frac{\partial C}{\partial t} = -\frac{\partial(v_x C)}{\partial x} - \frac{\partial(v_y C)}{\partial y} - \frac{\partial(v_z)}{\partial z} \tag{2.1}$$

where:

v_x, v_y, v_z = seepage or linear pore velocity, in coordinate directions x, y and z, ms^{-1}.

C = dissolved concentration of the contaminant species, gm^{-3}.

x, y, z = distance along the respective Cartesian coordinate axis, m.

t = time, s.

Seepage velocity is related to the specific discharge or Darcy velocity through the equations:

$$v_x = \frac{q_x}{\theta},\ v_y = \frac{q_y}{\theta},\ v_z = \frac{q_z}{\theta} \tag{2.2}$$

where:

q_x, q_y, q_z = Darcy velocities, in the directions x, y and z, ms^{-1} and

θ = porosity, dimensionless (porosity is a measure of void spaces in a material).

By substituting q_x, q_y and q_z in equation 2.1, the advective transport equation becomes:

$$\frac{\partial(\theta C)}{\partial t} = -\frac{\partial(q_x C)}{\partial x} - \frac{\partial(q_y C)}{\partial y} - \frac{\partial(q_z C)}{\partial z} \tag{2.3}$$

The transport equation is related to the groundwater flow equation through the Darcy's Law (Rushton, 2003):

$$q_x = -K_x \frac{\partial h}{\partial x},\ q_y = -K_y \frac{\partial h}{\partial y},\ q_z = -K_z \frac{\partial h}{\partial z} \tag{2.4}$$

where h = hydraulic head, m.

The hydraulic head is calculated by solving the partial differential equation for three-dimensional, fully saturated groundwater flow (Rushton, 2003):

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) + q_s = S_s \frac{\partial h}{\partial t} \tag{2.5}$$

where:

K_x, K_y, K_z = values of hydraulic conductivity along the directions x, y and z (hydraulic conductivity is a property of the porous medium which measures how easy it is for water to move through a material), ms^{-1}, and

S_s = specific storage, volume of water released from storage in a unit volume of aquifer per unit decline in head, m^{-1}.

The general advective transport equation 2.1 or 2.3 is suitable when the concentration and velocity vary in three dimensions without any fluid sources or sinks. We have assumed that neither water nor the contaminant is added to, or removed from, the aquifer.

A.2 Sources and Sinks

If there is a contaminant source through which contaminated water is added into the system or a sink through which water is withdrawn, the source is included in the advective transport equation 2.3 as:

$$\frac{\partial(\theta C)}{\partial t} = -\frac{\partial(q_x C)}{\partial x} - \frac{\partial(q_y C)}{\partial y} - \frac{\partial(q_z C)}{\partial z} + q_s C_s \qquad (2.6)$$

where:

q_s = volumetric flow rate per unit volume of the aquifer due to sources (positive) and sinks (negative), s^{-1}, and

C_s = concentration of the contaminant species in water that is added or removed, gm^{-3}.

A.3 Dispersion

Dispersion is the spreading of the contaminant over a wider region. Rather than moving with groundwater, dispersion occurs due to a departure from that movement. Dispersion is caused by (1) mechanical dispersion, a consequence of deviation of particle velocity from groundwater velocity and (2) molecular diffusion caused by concentration gradient. Generally, molecular diffusion is negligible compared to mechanical dispersion. Molecular diffusion is important only when groundwater flow velocity is very low. Hydrodynamic dispersion or dispersion refers to the sum of mechanical dispersion and molecular diffusion.

Dispersion is included in the transport equation using a dispersion tensor, D_{ij}. The dispersion tensor is calculated from the pore velocity and dispersivity which is a property of the porous medium. For the three-dimensional problem, the dispersion tensor is defined in the component form as:

$$D_{xx} = \frac{\alpha_L v_x^2}{|v|} + \frac{\alpha_T v_y^2}{|v|} + \frac{\alpha_T v_z^2}{|v|} + D^* \tag{2.7}$$

$$D_{yy} = \frac{\alpha_L v_y^2}{|v|} + \frac{\alpha_T v_x^2}{|v|} + \frac{\alpha_T v_z^2}{|v|} + D^* \tag{2.8}$$

$$D_{zz} = \frac{\alpha_L v_z^2}{|v|} + \frac{\alpha_T v_x^2}{|v|} + \frac{\alpha_T v_y^2}{|v|} + D^* \tag{2.9}$$

$$D_{xy} = D_{yx} = \frac{(\alpha_L - \alpha_T) v_x v_y}{|v|} \tag{2.10}$$

$$D_{xz} = D_{zx} = \frac{(\alpha_L - \alpha_T) v_x v_z}{|v|} \tag{2.11}$$

$$D_{yz} = D_{zy} = \frac{(\alpha_L - \alpha_T) v_y v_z}{|v|} \tag{2.12}$$

where:

D_{xx}, D_{yy}, D_{zz}, D_{xy}, D_{xz}, D_{yz} = components of the dispersion tensor, m^2s^{-1},

α_L = longitudinal dispersivity, m,

α_T = transverse dispersivity, m,

D^*= effective molecular diffusion coefficient, m^2s^{-1},

v_x, v_y, and v_z = components of the velocity vector along x, y, and z axes, ms^{-1}, and

$|v| = (v_x^2 + v_y^2 + v_z^2)^{½}$ = magnitude of the velocity vector, ms^{-1}.

The dispersion tensor defined by longitudinal and transverse dispersivities is valid only for isotropic media. For anisotropic media it requires five independent dispersivities.

By incorporating the dispersion term in equation 2.6, we get the equation which describes advective and dispersive solute transport in groundwater:

$$\frac{\partial(\theta C)}{\partial t}=\frac{\partial}{\partial x}\left(\theta D_{xx}\frac{\partial C}{\partial x}+\theta D_{xy}\frac{\partial C}{\partial y}+\theta D_{xz}\frac{\partial C}{\partial z}\right)+\frac{\partial}{\partial y}\left(\theta D_{yx}\frac{\partial C}{\partial x}+\theta D_{yy}\frac{\partial C}{\partial y}+\theta D_{yz}\frac{\partial C}{\partial z}\right)+ \\ \frac{\partial}{\partial z}\left(\theta D_{zx}\frac{\partial C}{\partial x}+\theta D_{zy}\frac{\partial C}{\partial y}+\theta D_{zz}\frac{\partial C}{\partial z}\right)+\frac{\partial(q_x C)}{\partial x}+\frac{\partial(q_y C)}{\partial y}+\frac{\partial(y_z C)}{\partial z}+\sum_s q_s C_s \tag{2.13}$$

A.4 Chemical Reaction

There are two types of chemical reactions that affect solute transport in groundwater: (1) chemical reactions that are sufficiently fast and reversible so that local equilibrium can be assumed and (2) chemical reactions that are insufficiently fast and/or irreversible so that local equilibrium assumption cannot be applied. The chemical reactions that are commonly included in the transport simulations are equilibrium-controlled or rate-limited sorption reactions (transfer of mass between the dissolved phase and the solid matrix of the porous medium) and kinetic reactions such as first-order decay.

The effects of chemical reactions are included in the advection-dispersion equation 2.14 using a chemical sink/source term, $\sum_n R_n$, which represents the rate of change in solute mass due to n = 1,2, …, N chemical reactions. The equation which governs the transport of a contaminant in groundwater due to advection, dispersion and chemical reaction is:

$$\frac{\partial(\theta C)}{\partial t}=\frac{\partial}{\partial x}\left(\theta D_{xx}\frac{\partial C}{\partial x}+\theta D_{xy}\frac{\partial C}{\partial y}+\theta D_{xz}\frac{\partial C}{\partial z}\right)+\frac{\partial}{\partial y}\left(\theta D_{yx}\frac{\partial C}{\partial x}+\theta D_{yy}\frac{\partial C}{\partial y}+\theta D_{yz}\frac{\partial C}{\partial z}\right)+ \\ \frac{\partial}{\partial z}\left(\theta D_{zx}\frac{\partial C}{\partial x}+\theta D_{zy}\frac{\partial C}{\partial y}+\theta D_{zz}\frac{\partial C}{\partial z}\right)+\frac{\partial(q_x C)}{\partial x}+\frac{\partial(q_y C)}{\partial y}+\frac{\partial(y_z C)}{\partial z}+\sum_s q_s C_s+\sum_n R_n \tag{2.14}$$

The chemical sink source term for equilibrium-controlled sorption and first-order irreversible rate reactions can be written as:

$$\sum_n R_n = -\rho_b \frac{\partial C'}{\partial t} - \lambda_1 \theta C - \lambda_2 \rho_b C' \tag{2.15}$$

where:

ρ_b = bulk density of the porous medium, gm^{-1},

C' = sorbed concentration, a function of the dissolved concentration *C* as defined by the sorption isotherm (an isotherm is a plot of the dissolved concentration *C* versus the sorbed concentration *C'*), gg^{-1},

λ_1 = reaction rate constant for the dissolved phase, s^{-1}, and

λ_2 = reaction rate constant for the sorbed (solid) phase, s^{-1}.

By substituting $\sum_n R_n$ in the advective, dispersive and reactive transport equation 2.14 we get:

$$\begin{aligned}\frac{\partial(\theta C)}{\partial t} &= \frac{\partial}{\partial x}\left(\theta D_{xx}\frac{\partial C}{\partial x} + \theta D_{xy}\frac{\partial C}{\partial y} + \theta D_{xz}\frac{\partial C}{\partial z}\right) + \frac{\partial}{\partial y}\left(\theta D_{yx}\frac{\partial C}{\partial x} + \theta D_{yy}\frac{\partial C}{\partial y} + \theta D_{yz}\frac{\partial C}{\partial z}\right) + \\ &\frac{\partial}{\partial z}\left(\theta D_{zx}\frac{\partial C}{\partial x} + \theta D_{zy}\frac{\partial C}{\partial y} + \theta D_{zz}\frac{\partial C}{\partial z}\right) + \frac{\partial(q_x C)}{\partial x} + \frac{\partial(q_y C)}{\partial y} + \frac{\partial(y_z C)}{\partial z} + \sum_s q_s C_s - \\ &\rho_b \frac{\partial C'}{\partial t} - \lambda_1 \theta C - \lambda_2 \rho_b C'\end{aligned} \tag{2.16}$$

Assuming porosity θ does not change over time, equation 2.17 can be rearranged as:

$$\begin{aligned}\theta R\frac{\partial(C)}{\partial t} &= \frac{\partial}{\partial x}\left(\theta D_{xx}\frac{\partial C}{\partial x} + \theta D_{xy}\frac{\partial C}{\partial y} + \theta D_{xz}\frac{\partial C}{\partial z}\right) + \frac{\partial}{\partial y}\left(\theta D_{yx}\frac{\partial C}{\partial x} + \theta D_{yy}\frac{\partial C}{\partial y} + \theta D_{yz}\frac{\partial C}{\partial z}\right) + \\ &\frac{\partial}{\partial z}\left(\theta D_{zx}\frac{\partial C}{\partial x} + \theta D_{zy}\frac{\partial C}{\partial y} + \theta D_{zz}\frac{\partial C}{\partial z}\right) + \frac{\partial(q_x C)}{\partial x} + \frac{\partial(q_y C)}{\partial y} + \frac{\partial(y_z C)}{\partial z} + \\ &\sum_s q_s C_s - \lambda_1 \theta C - \lambda_2 \rho_b C'\end{aligned} \tag{2.17}$$

where $R = 1 + \frac{\rho_b}{\theta}\left(\frac{\partial C'}{\partial C}\right)$ known as the Retardation Factor, is dimensionless.

Equation 2.17 is the mass balance equation which states that the change in mass storage (both dissolved and sorbed phases) at any given time is equal to the difference in mass inflow and outflow due to advection, dispersion, equilibrium-controlled sorption, first-order irreversible rate reactions and sink/source.

Appendix B

HYPOTHETICAL RIVER CATCHMENT MODEL

This appendix provides the details of the hypothetical river catchment model used to demonstrate the physical characteristics of the problem addressed in this thesis, the way nonpoint source nitrate pollution spreads over time and space.

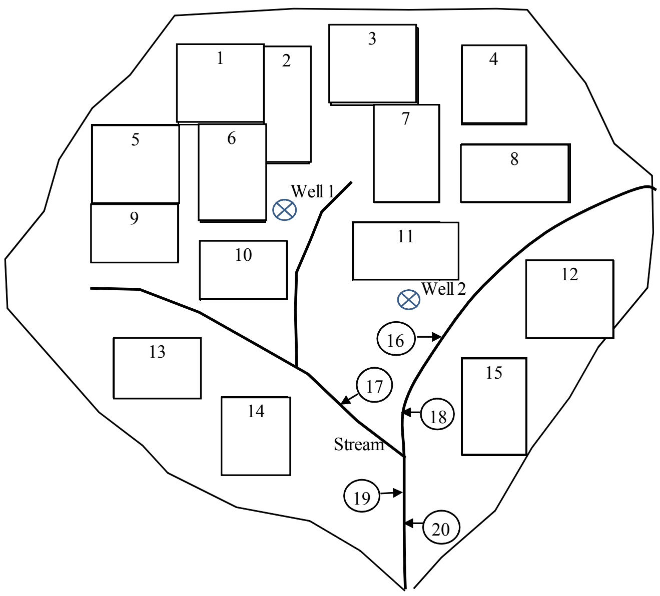

Figure B.1: Hypothetical river catchment.

This catchment, which drains towards a stream, has a maximum length of is 6 km from north to south and a maximum width of 6 km from east to west. The lower half (southern part) of the catchment is bounded by impermeable rocks (no-flow boundaries) on the east and west sides. The upper (northern) boundary is considered as a fixed head boundary with a hydraulic head of 19.5 m. The aquifer thickness is 20 m. A plan view of the study site is shown in Figure B.1. Rectangles indicate nonpoint sources (farms) and the circles indicate point sources. The two crossed circles indicate groundwater monitoring wells. We assume nitrate losses from farms occur due to leaching, and runoff losses are negligible. To understand the fate of leached nitrates, we model advective, dispersive, and reactive nitrate transport in groundwater with standard computer codes MODFLOW and MT3D, using Visual MODFLOW and a GUI to interface with the codes. The hydro-geological parameters used in the simulations are given in Table B.1.

Parameter	**Value**
Horizontal hydraulic conductivity	0.0006 m/s
Vertical hydraulic conductivity	0.0001 m/s
Storage coefficient	0.0001 1/m
Recharge	100 mm/year
Effective porosity	0.2
Specific yield	0.2
Total porosity	0.3
Longitudinal dispersivity	5 m
Ratio: H/L dispersivity	0.1
Ratio: V/L dispersivity	0.01
First order decay coefficient	0.00002 1/day
Molecular diffusion coefficient	0.00005
Model Grid	
Cell length	200 m
Cell width	200 m
Cell thickness	20 m
Number of layers	1
Simulation period	10,978 days (30 years)

Table B.1: Properties of the aquifer underlying the hypothetical catchment.

Using the model, we simulated 1 kg nitrate loading from each farm during one year (2010). The whole simulation period was set to 30 years (from 2010 to 2039) to observe the effects of one year's loading over the next 30 years. From each farm simulation, we observed (1) how much nitrate is discharged into the stream in each year and (2) by how much the concentration in each well increases in each year, due to 1 kg nitrate loading from the farm in the first year (2010). The results are given in Table B.2.

Year	Farm									
	1	2	3	4	5	6	7	8	9	10
2010	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.024	0.038
2011	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.065	0.101	0.113
2012	0.000	0.030	0.000	0.000	0.000	0.029	0.019	0.103	0.130	0.129
2013	0.000	0.051	0.000	0.000	0.000	0.053	0.024	0.114	0.124	0.121
2014	0.000	0.066	0.018	0.000	0.000	0.071	0.027	0.110	0.107	0.106
2015	0.000	0.075	0.026	0.000	0.024	0.084	0.030	0.099	0.090	0.090
2016	0.000	0.078	0.032	0.000	0.033	0.089	0.031	0.086	0.074	0.075
2017	0.000	0.077	0.038	0.019	0.041	0.088	0.032	0.072	0.060	0.061
2018	0.024	0.073	0.041	0.025	0.047	0.083	0.032	0.060	0.048	0.049
2019	0.032	0.068	0.043	0.030	0.053	0.075	0.033	0.049	0.039	0.039
2020	0.039	0.061	0.044	0.034	0.056	0.066	0.033	0.039	0.031	0.031
2021	0.045	0.054	0.044	0.038	0.059	0.057	0.033	0.031	0.024	0.024
2022	0.050	0.048	0.043	0.040	0.059	0.047	0.033	0.025	0.000	0.000
2023	0.053	0.041	0.041	0.042	0.058	0.039	0.033	0.000	0.000	0.000
2024	0.055	0.035	0.038	0.043	0.056	0.032	0.032	0.000	0.000	0.000
2025	0.055	0.030	0.036	0.043	0.052	0.026	0.032	0.000	0.000	0.000
2026	0.054	0.025	0.033	0.042	0.048	0.020	0.031	0.000	0.000	0.000
2027	0.052	0.020	0.030	0.041	0.044	0.000	0.030	0.000	0.000	0.000
2028	0.049	0.000	0.028	0.039	0.040	0.000	0.029	0.000	0.000	0.000
2029	0.045	0.000	0.026	0.037	0.035	0.000	0.028	0.000	0.000	0.000
2030	0.041	0.000	0.023	0.034	0.031	0.000	0.026	0.000	0.000	0.000
2031	0.037	0.000	0.022	0.032	0.026	0.000	0.025	0.000	0.000	0.000
2032	0.033	0.000	0.020	0.030	0.023	0.000	0.024	0.000	0.000	0.000
2033	0.029	0.000	0.018	0.027	0.000	0.000	0.022	0.000	0.000	0.000
2034	0.026	0.000	0.017	0.025	0.000	0.000	0.021	0.000	0.000	0.000
2035	0.022	0.000	0.016	0.022	0.000	0.000	0.020	0.000	0.000	0.000
2036	0.000	0.000	0.015	0.020	0.000	0.000	0.018	0.000	0.000	0.000
2037	0.000	0.000	0.000	0.018	0.000	0.000	0.017	0.000	0.000	0.000
2038	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2039	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Year	Farm				
	11	12	13	14	15
2010	0.000	0.000	0.000	0.000	0.000
2011	0.016	0.020	0.000	0.000	0.000
2012	0.025	0.032	0.000	0.000	0.000
2013	0.033	0.039	0.016	0.000	0.020
2014	0.039	0.042	0.021	0.000	0.027
2015	0.044	0.043	0.026	0.000	0.033
2016	0.046	0.043	0.029	0.020	0.038
2017	0.048	0.041	0.032	0.024	0.042
2018	0.047	0.039	0.033	0.027	0.044
2019	0.047	0.036	0.034	0.029	0.046
2020	0.045	0.034	0.035	0.031	0.046

2021	0.043	0.032	0.035	0.033	0.046
2022	0.041	0.029	0.034	0.034	0.044
2023	0.038	0.027	0.034	0.035	0.043
2024	0.036	0.025	0.032	0.035	0.041
2025	0.033	0.024	0.031	0.035	0.038
2026	0.031	0.022	0.030	0.035	0.036
2027	0.029	0.021	0.028	0.034	0.033
2028	0.026	0.020	0.027	0.034	0.031
2029	0.024	0.019	0.025	0.032	0.028
2030	0.022	0.018	0.024	0.031	0.025
2031	0.020	0.017	0.022	0.030	0.023
2032	0.000	0.016	0.021	0.028	0.021
2033	0.000	0.016	0.019	0.027	0.019
2034	0.000	0.015	0.018	0.025	0.000
2035	0.000	0.014	0.017	0.023	0.000
2036	0.000	0.014	0.015	0.022	0.000
2037	0.000	0.000	0.014	0.020	0.000
2038	0.000	0.000	0.000	0.018	0.000
2039	0.000	0.000	0.000	0.017	0.000

Table B.2: Amount of nitrate (kg) delivered to the stream from 1 kg nitrate loading in 2010 from each farm.

Appendix C

BID FUNCTIONS

The purpose of this appendix is to demonstrate how to use available information to estimate the farm profit functions and to calculate the bids. We show how to calculate the bids for a dairy farm using the “gross \$:N relationships”, presented by Woods et al. (2004) (Table 9.2). Those relationships have been estimated considering the farms in the Waikato region of New Zealand, and therefore the estimated marginal profit function are not generally applicable.

Woods et al. (2004) expressed nitrate leaching (*N-loading*) and operating profit (*profit*) from dairy as a function of stocking rate (*cows*). These relationships are given by equations C1 and C2 below.

$$\textit{N-loading}\ (\text{kg/ha/year}) = 7.6\times \textit{cows}^{1.785} \tag{C1}$$

$$\textit{profit}\ (\$/\text{ha}) = 729\times \textit{cows} - 235 \tag{C2}$$

By re-arranging C1, $\textit{cows}\ (\text{cows/ha}) = (\textit{N-loading}/7.6)^{1/1.785}$ (C3)

Applicable range: $1 \leq \textit{cows} \leq 4$

In Table C.1, we calculate the incremental profit from each 1 kg of nitrate loading based on the above relationships. To calculate the marginal profit, we first selected the range of the variable *N-loading* so that the range of the variable *cows* is from 1 to 4, because the relationships are valid for this range only (first column). Then we calculated the relevant values for the variable *cows* based on equation C3 (second column). Then the *profit* corresponding to each *N-loading* was calculated from equation C2 (third column). The incremental profit from each kg of *N-loading* was calculated from the differences in *profit*.

From the incremental profit generated from each incremental unit of nitrate loading, a marginal profit curve for a dairy farm can be drawn as in Figure C.1.

The marginal profit function can be approximated to a piece-wise linear function as shown in Figure C.2. Based on the piece-wise linearization, a risk-averse farm would bid $41 for the first 13 kg, $33 for the next 8 kg, and so on, as given in Table 9.1.

N-loading	*cows*	*Profit*	Incremental profit
8	1.03	$515.25	-
9	1.10	$566.43	$51.18
10	1.17	$615.16	$48.73
11	1.23	$661.78	$46.63
12	1.29	$706.58	$44.80
13	1.35	$749.76	$43.18
14	1.41	$791.51	$41.75
15	1.46	$831.96	$40.45
16	1.52	$871.25	$39.28
17	1.57	$909.46	$38.22
18	1.62	$946.70	$37.24
19	1.67	$983.04	$36.34
20	1.72	$1,018.55	$35.51
21	1.77	$1,053.29	$34.74
22	1.81	$1,087.31	$34.02
23	1.86	$1,120.65	$33.34
24	1.90	$1,153.36	$32.71
25	1.95	$1,185.48	$32.12
26	1.99	$1,217.03	$31.56
27	2.03	$1,248.06	$31.03
28	2.08	$1,278.59	$30.53
29	2.12	$1,308.64	$30.05
30	2.16	$1,338.23	$29.60
31	2.20	$1,367.40	$29.17
32	2.24	$1,396.16	$28.76
33	2.28	$1,424.52	$28.36
34	2.31	$1,452.51	$27.99
35	2.35	$1,480.14	$27.63
36	2.39	$1,507.42	$27.28
37	2.43	$1,534.37	$26.95
38	2.46	$1,561.00	$26.63
39	2.50	$1,587.33	$26.33
40	2.54	$1,613.36	$26.03
41	2.57	$1,639.11	$25.75
42	2.61	$1,664.58	$25.47
43	2.64	$1,689.79	$25.21

44	2.67	$1,714.74	$24.95
45	2.71	$1,739.44	$24.70
46	2.74	$1,763.90	$24.46
47	2.78	$1,788.13	$24.23
48	2.81	$1,812.13	$24.00
49	2.84	$1,835.92	$23.78
50	2.87	$1,859.49	$23.57
51	2.91	$1,882.86	$23.37
52	2.94	$1,906.02	$23.16
53	2.97	$1,928.99	$22.97
54	3.00	$1,951.77	$22.78
55	3.03	$1,974.37	$22.60
56	3.06	$1,996.78	$22.42
57	3.09	$2,019.02	$22.24
58	3.12	$2,041.09	$22.07
59	3.15	$2,062.99	$21.90
60	3.18	$2,084.73	$21.74
61	3.21	$2,106.31	$21.58
62	3.24	$2,127.74	$21.43
63	3.27	$2,149.01	$21.27
64	3.30	$2,170.14	$21.13
65	3.33	$2,191.12	$20.98
66	3.36	$2,211.96	$20.84
67	3.38	$2,232.66	$20.70
68	3.41	$2,253.23	$20.57
69	3.44	$2,273.66	$20.43
70	3.47	$2,293.97	$20.30
71	3.50	$2,314.14	$20.18
72	3.52	$2,334.19	$20.05
73	3.55	$2,354.12	$19.93
74	3.58	$2,373.93	$19.81
75	3.61	$2,393.63	$19.69
76	3.63	$2,413.21	$19.58
77	3.66	$2,432.67	$19.46
78	3.69	$2,452.02	$19.35
79	3.71	$2,471.27	$19.25
80	3.74	$2,490.41	$19.14
81	3.76	$2,509.44	$19.03
82	3.79	$2,528.37	$18.93
83	3.82	$2,547.20	$18.83
84	3.84	$2,565.93	$18.73
85	3.87	$2,584.56	$18.63
86	3.89	$2,603.10	$18.54
87	3.92	$2,621.54	$18.44
88	3.94	$2,639.89	$18.35
89	3.97	$2,658.14	$18.26
90	3.99	$2,676.31	$18.17

Table C.1: Incremental profit from kg nitrate loading.

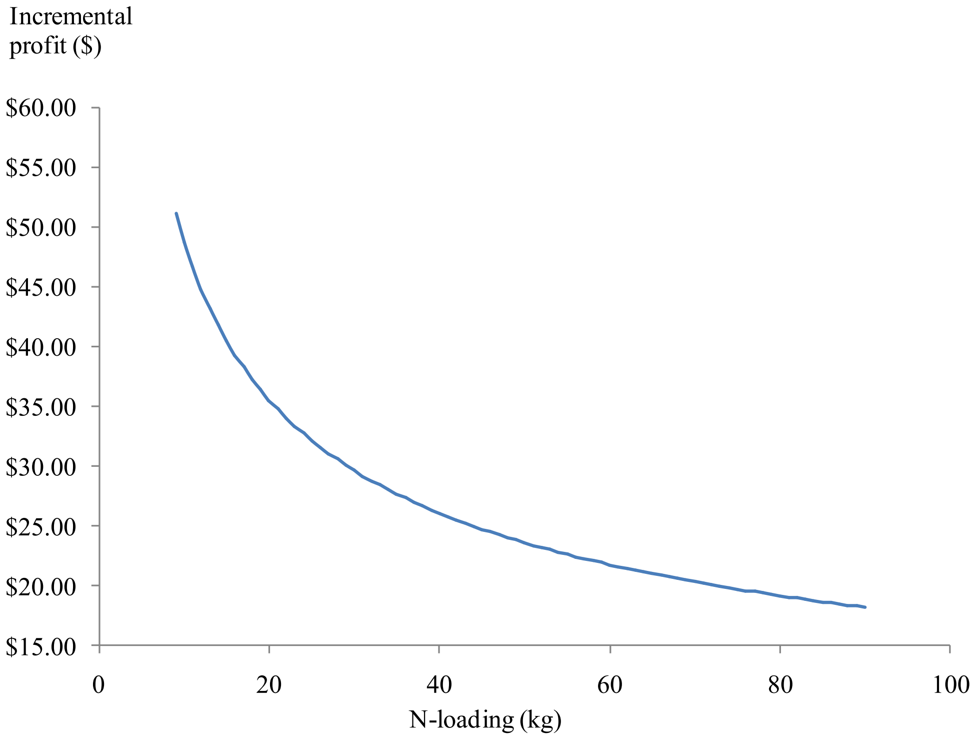

Figure C.1: Marginal profit function.

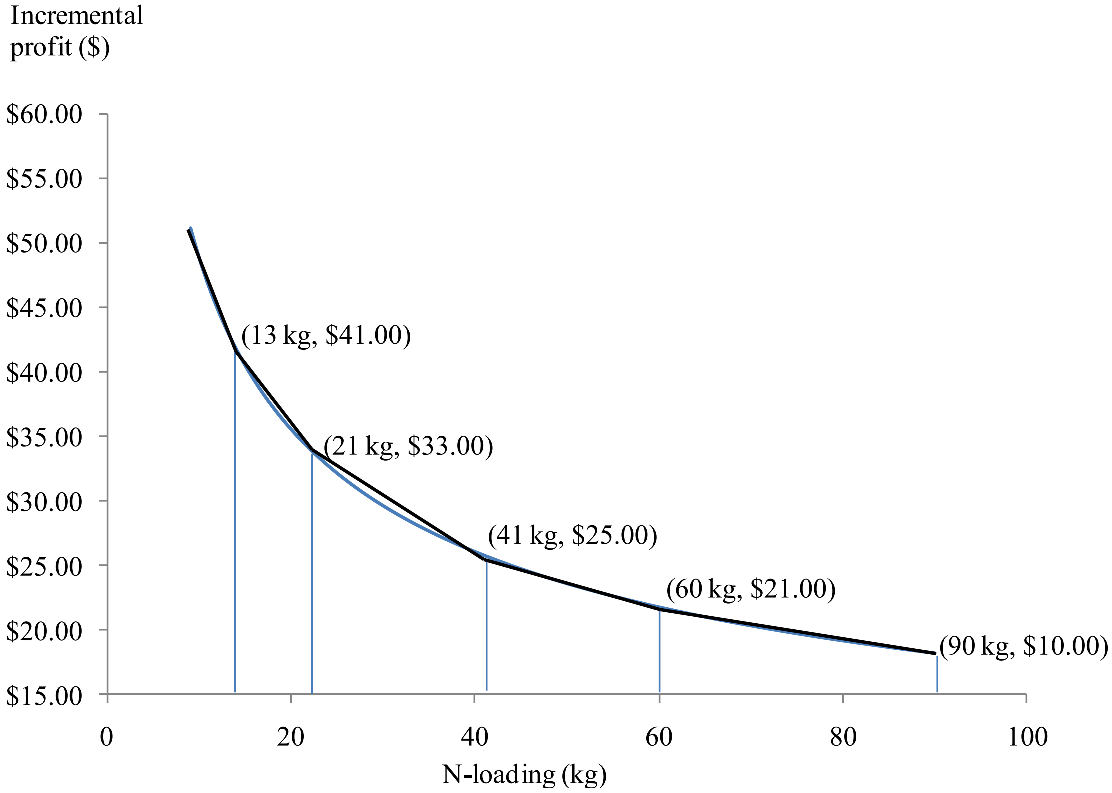

Figure C.2: Piece-wise linearization of the marginal profit function.

Appendix D

EDENDALE AQUIFER MODEL

This discussion is based on a report and an accompanied nitrate-N (nitrogen in the form of nitrate) transport simulation model produced by AquaFirma Ltd for the Southland Regional Council (Rekker 1998), as part of a multi-disciplinary project on the nonpoint source effects on groundwater and surface water quality in the Southland Region of New Zealand. The main purpose of the report and the model was to study the effects of possible land use intensification in Southland on the quality of groundwater and groundwater-fed surface water bodies in the region.

The Edendale aquifer which underlies the catchment area drains from north-west to south-east, towards the Mataura River which flows from north to south along the eastern margin of the aquifer (Figure D.1). Hence, the model domain includes only a part of the Mataura River Catchment. The western margin of the aquifer is covered by the Edendale Hills. The river receives groundwater flux directly and also indirectly via springs as shown in the cross-sectional view of the aquifer in Figure D.2.

The purpose of the nitrate-N transport model developed using MODFLOW and MT3D was to study the effects of agricultural intensification on the groundwater nitrate-N levels and the nitrate-N levels in the springs and the Mataura River. The model was used to predict the effects of different land use intensification scenarios (for example, converting all pasture land to high intensity dairy) relative to the current (as at 1998) situation.

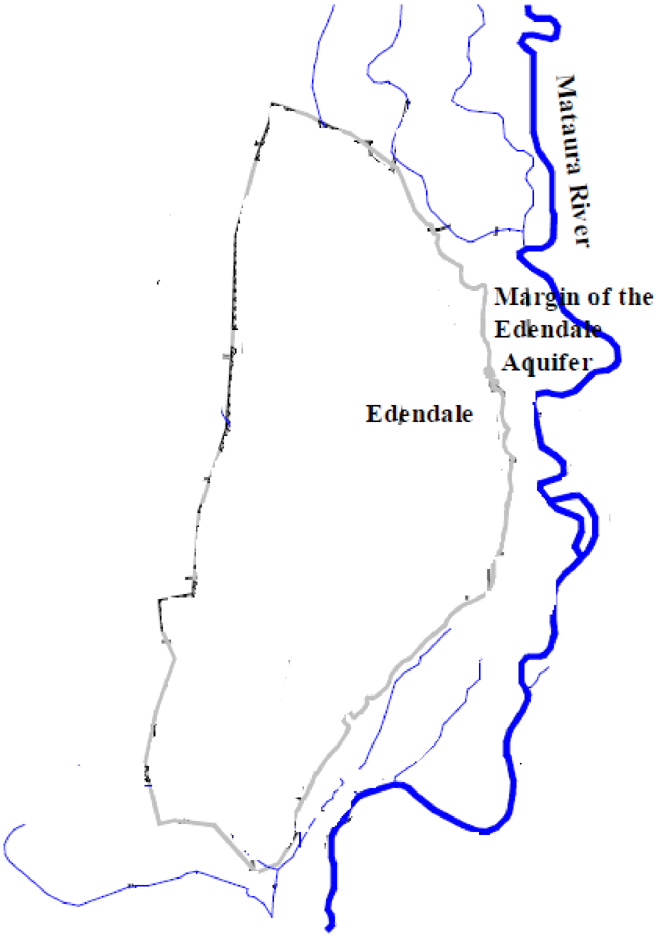

Figure D.1: Edendale aquifer setting. Source: Rekker (1998).

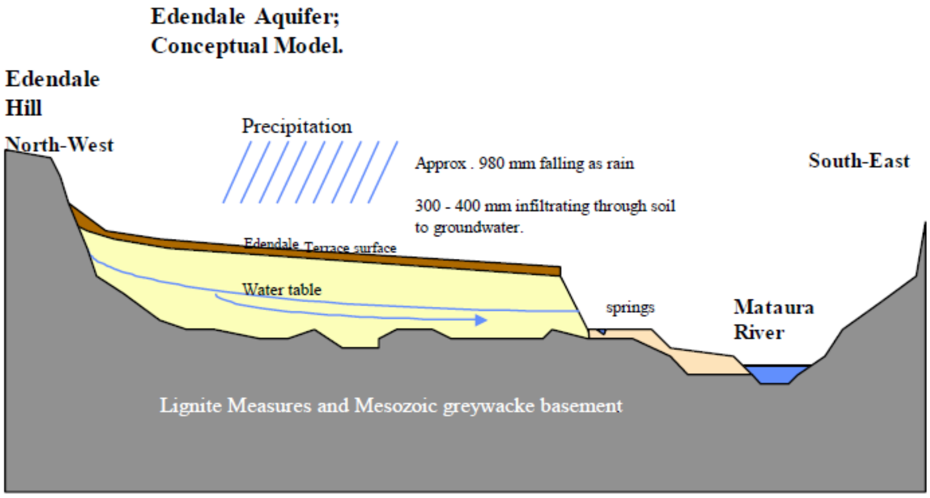

Figure D.2: Edendale aquifer cross-sectional view. Source: Rekker (1998).

The pre-1998 land use distribution in the region, as given in the report and the model, is shown in Figure D.3. Areal nitrate-N loading for the base case (pre-1998) scenario has been assigned based on twelve recognized land use classes as shown in the figure (for example, 56 kg/ha/year from high intensity dairy and 1.7 kg/ha/year for low intensity sheep).

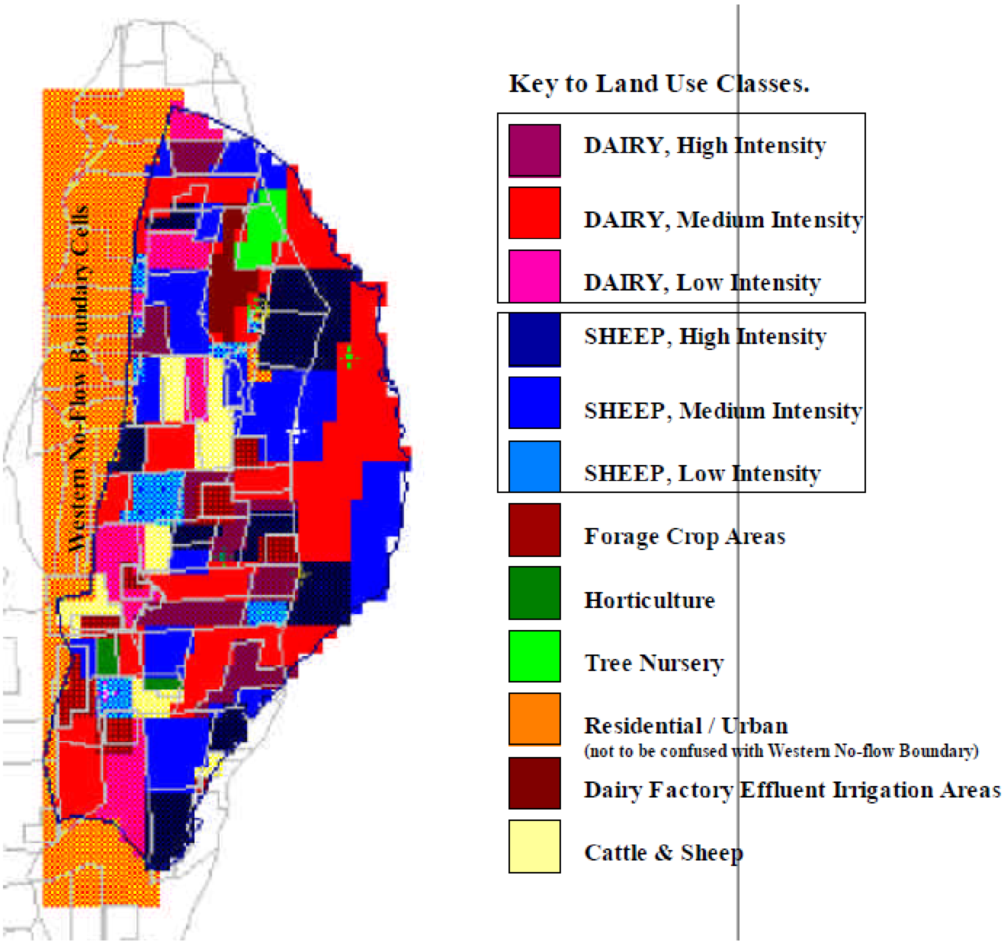

Figure D.3: Land use distribution for the base case (pre-1998) scenario. Source: Rekker (1998).

We used this nitrate-N transport model to demonstrate a tradable permit program to allocate nitrate loading permits among the farms in the region. Even though we used the original MODFLOW and MT3D simulation models without making any changes to the hydro-geological data, since we use it for a different purpose, we had to make a few assumptions.

Receptors: First, we assume that the Mataura River is the only receptor concerned (R=1). Since groundwater discharges through the springs eventually flow down to the river (the time delay is ignored), the total mass nitrate-N discharge into the river, directly or indirectly via springs, is a good indicator of nitrate pollution in the region.

Receptor capacity: Assuming that the nitrate-N discharge into the river was in equilibrium with the land use nitrate loading as at 1998, annual mass nitrate-N discharge into the stream from pre-1998 land use is considered as the maximum acceptable nitrate discharge into the river (nitrate intake capacity of the river). The receptor capacity was calculated by simulating the pre-1998 nitrate loading over a period of 50 years (until equilibrium is achieved approximately) as 120,647 kg/year[54] (C^{SD}_1=120,647 kg/year).

Farms: We assumed 62 farms so that they collectively cover the whole pre-1998 land use area. However, the farm boundaries do not correspond to either the actual (present) property boundaries or the property boundaries given in the original model. We defined the farms mainly based on the land use type. The hypothetical property boundary map is given in Figure D.4. To demonstrate the results of a trading program, we categorized the 62 farms into three groups (dairy, sheep, and crop) based on their pre-1998 land use type, and assigned a single marginal profit function of nitrate loading (kg/ha/year) and thus a single set of bids for each group. For example, all dairy farms (the properties in which most of the area was originally recognized as dairy land) submit the same set of bids. The assigned groups and other information assumed for the farm are given in Tables D.1 and D.2. The bid function assigned for each group is given in Table 9.2 of Chapter 9.

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[54] The value is below the annual mass load 152,942 kg/year estimated in the report, for three reasons. First about 4-5% of the load is removed from the groundwater abstraction well. Second, we reduced the areal mass nitrate-N load from the effluent irrigation area and residential area to 80 and 1.7 kg/ha/year respectively, as recommended in the report (the original values were 178 and 16.3 kg/ha/year). Third, it would take a few more years to reach equilibrium because the nitrate load from upstream farms 1 and 2 takes more than 50 years to be delivered to the river completely (as shown in the response matrix in Table D.3).

Response Matrix: Using the original nitrate-N transport model, we obtained response coefficients for each farm assuming each farm location as a node. Since the river is the only receptor concerned, we simulated 1 kg nitrate-N loading from each farm during one year, and obtained the mass nitrate discharge into the river (and springs modelled as drains in MT3D) in each of the next 50 years (including the loading year). We used some VB.NET codes to read the output files produced by MT3D, to convert the units and calculate the response coefficients, and to write the response matrix into MS Excel. The response matrix is given in Table D.3.

Available Capacity: Currently available capacity is the difference between the nitrate intake capacity of the river (120,647 kg/year) and the mass nitrate load expected to reach the river from groundwater nitrate storage, assuming no other unmanageable sources. Available capacity depends on all previous land uses. For the demonstration of a tradable permit program to be started from 2011, we considered two sets of available capacities calculated based on two prior land use scenarios, sustainable land use and intensive land use.

The sustainable land use scenario assumes that the pre-1998 land use has been continued until 2010. To estimate the available capacities for this scenario, we simulated the pre-1998 nitrate loading over a period of 50 years to obtain the current (as at 2010) concentration distribution in groundwater. Then we simulated the current concentration distribution (as initial concentration) over a period of another 50 years to obtain the mass nitrate-N load expected to be delivered to the river from current nitrate-N storage in groundwater. The results and the calculated tradable capacities are given in Table D.4. Since the nitrate intake capacity of the river was estimated based on pre-1998 nitrate loading, the available capacity is always positive.

The intensive land use scenario assumes that all dairy and sheep land were converted to high intensity farming after 1998. To estimate the available capacities for this scenario, we ran the simulation for a 50 year period with pre-1998 nitrate loading over the first 48 years, and intensive loading over the next 12 years. We obtained the output concentration distribution file, and again simulated it as the initial concentration for a period of 50 years. The results and the calculated tradable capacities are given in

Table D.4. Since the nitrate intake capacity of the river was estimated based on pre-1998 nitrate loading, and the nitrate loading has been significantly increased over the last 12 years, the available capacity is zero in the early years.

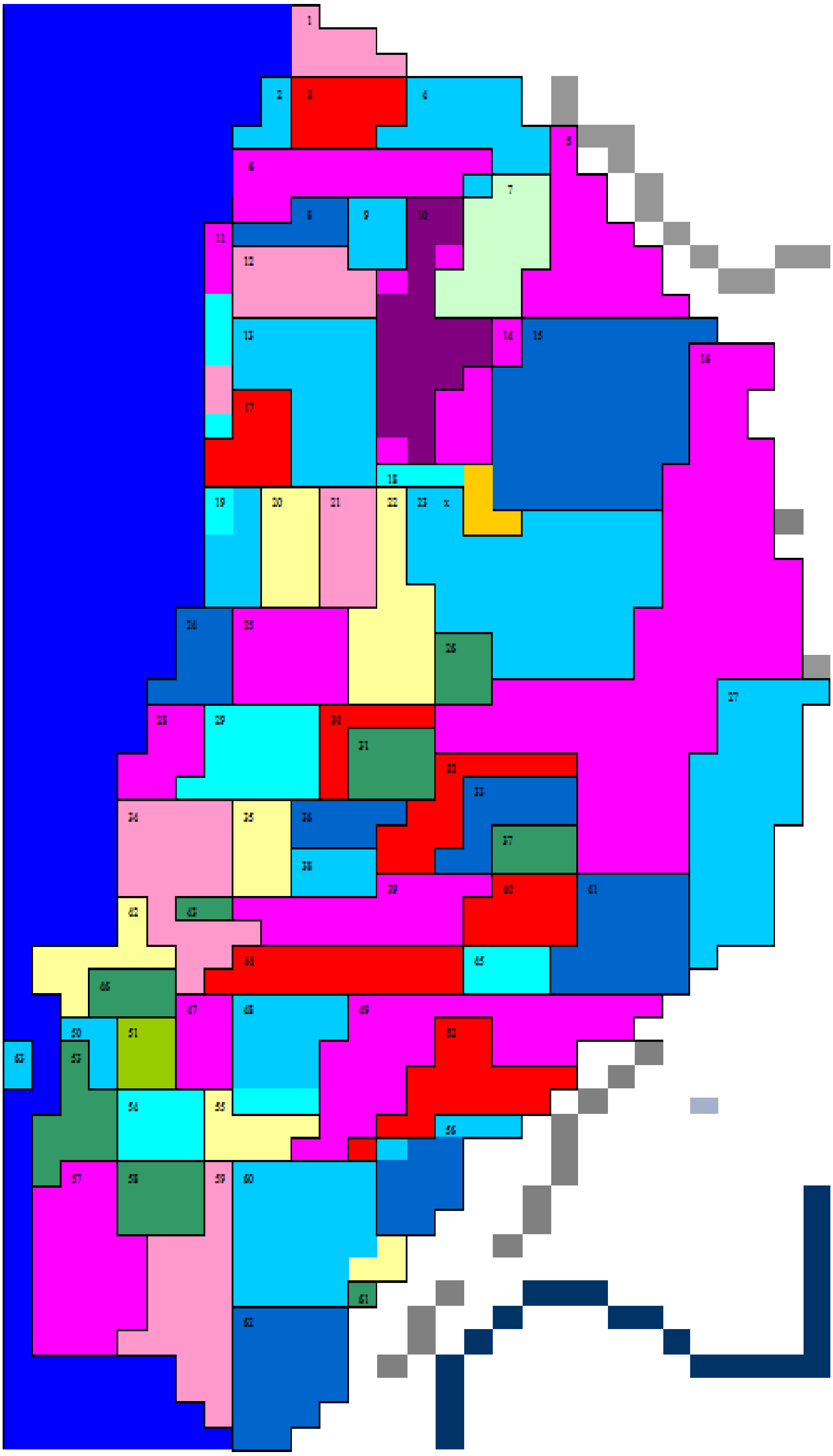

Figure D.4: Hypothetical farm boundary map.

Pre-1998 Land use type	Group	Colour	Code	Nitrate Loading (kg/ha/year)
Dairy-High	Dairy		DH	53.3
Dairy-Medium	Dairy		DM	22.6
Dairy-Low	Dairy		DL	11.9
Sheep-High	Sheep		SH	10.8
Sheep-Medium	Sheep		SM	3.6
Sheep-Low	Sheep		SL	1.7
Forage	Crop		F	79.9
Horticulture	Crop		H	1.6
Tree Nursery	Crop		T	15.7
Residential/Urban	Crop		R	1.7
Effluent Irrigation	Dairy		E	80.0
Sheep & Cattle	Sheep		SC	10.5

Table D.1: Pre-1998 land use types, nitrate loading, and the groups assigned.

Farm	Pre-1998 land use type	Area (ha)	Farm	Pre-1998 land use type	Area (ha)
1	DL	50	36	SH	43.75
2	SM	25	37	F	37.5
3	DH	62.5	38	SM	37.5
4	SM	106.25	39	DM	118.75
5	DM	150	40	DH	68.75
6	DM	118.75	41	SH	137.5
7	T	112.5	42	SC	62.5
8	SH	37.5	43	F	12.5
9	SM	37.5	44	DH	106.25
10	E	168.75	45	SL	37.5
11	SL	56.25	46	F	37.5
12	DL	87.5	47	DM	50
13	SM	168.75	48	SM	87.5
14	DM	56.25	49	DM	225
15	SH	331.25	50	SM	25
16	DM	656.25	51	H	37.5
17	DH	62.5	52	DH	112.5
18	SL	43.75	53	F	68.75
19	SM	62.5	54	SL	56.25
20	SC	62.5	55	SC	50
21	DL	62.5	56	SH	87.5
22	SC	112.5	57	DM	168.75

23	SM	325	58	F	56.25
24	SH	56.25	59	DL	150
25	DM	100	60	SM	193.75
26	F	37.5	61	F	6.25
27	SM	237.5	62	SH	131.25
28	DM	56.25			
29	SL	106.25			
30	DH	43.75			
31	F	56.25			
32	DH	81.25			
33	SH	68.75			
34	DL	150			
35	SC	50			

Table D.2: Hypothetical farms, areas, and land use types.

Delay	Node *n* (Farm *f*)										
d	1	2	3	4	5	6	7	8	9	10	11
0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0.001	0	0	0	0	0	0
2	0	0	0	0	0.015	0	0	0	0	0	0
3	0	0	0	0	0.056	0	0	0.001	0	0	0
4	0	0	0	0	0.107	0	0	0.009	0	0.001	0
5	0	0	0	0.001	0.139	0	0.004	0.03	0	0.004	0
6	0	0	0	0.005	0.144	0.001	0.015	0.063	0	0.009	0
7	0	0	0	0.013	0.13	0.003	0.039	0.098	0	0.017	0
8	0	0	0	0.026	0.107	0.007	0.073	0.121	0	0.028	0
9	0	0	0	0.043	0.082	0.012	0.107	0.127	0	0.039	0.001
10	0	0	0	0.06	0.061	0.018	0.13	0.116	0.002	0.049	0.002
11	0	0	0.001	0.073	0.044	0.023	0.133	0.096	0.005	0.054	0.005
12	0	0	0.002	0.082	0.032	0.027	0.121	0.075	0.012	0.057	0.011
13	0.001	0	0.004	0.085	0.023	0.03	0.1	0.056	0.023	0.057	0.02
14	0.001	0.001	0.007	0.084	0.017	0.033	0.077	0.041	0.037	0.054	0.031
15	0.002	0.001	0.011	0.078	0.012	0.037	0.056	0.031	0.052	0.051	0.044
16	0.003	0.003	0.017	0.071	0.009	0.041	0.039	0.024	0.066	0.046	0.057
17	0.005	0.005	0.024	0.062	0.006	0.046	0.028	0.019	0.076	0.041	0.07
18	0.007	0.008	0.032	0.054	0.005	0.051	0.02	0.015	0.082	0.036	0.079
19	0.009	0.013	0.04	0.045	0.003	0.055	0.015	0.012	0.083	0.03	0.085
20	0.012	0.018	0.048	0.038	0.002	0.058	0.011	0.01	0.081	0.025	0.086
21	0.016	0.024	0.056	0.031	0.002	0.059	0.008	0.008	0.076	0.021	0.084
22	0.019	0.031	0.061	0.026	0.001	0.058	0.006	0.006	0.068	0.017	0.077
23	0.023	0.037	0.065	0.021	0.001	0.056	0.005	0.004	0.06	0.013	0.069
24	0.027	0.044	0.066	0.017	0.001	0.052	0.003	0.003	0.051	0.01	0.06
25	0.031	0.049	0.066	0.014	0	0.047	0.002	0.002	0.042	0.008	0.05
26	0.034	0.054	0.064	0.011	0	0.042	0.002	0.002	0.034	0.006	0.041
27	0.038	0.057	0.061	0.009	0	0.037	0.001	0.001	0.026	0.005	0.033
28	0.039	0.058	0.055	0.007	0	0.031	0.001	0.001	0.02	0.003	0.025
29	0.042	0.06	0.051	0.006	0	0.026	0.001	0.001	0.015	0.002	0.019
30	0.042	0.057	0.044	0.005	0	0.021	0	0	0.011	0.002	0.014

31	0.044	0.057	0.04	0.004	0	0.017	0	0	0.008	0.001	0.011
32	0.042	0.052	0.034	0.003	0	0.013	0	0	0.006	0.001	0.007
33	0.042	0.05	0.029	0.002	0	0.01	0	0	0.004	0.001	0.005
34	0.04	0.044	0.024	0.002	0	0.008	0	0	0.003	0	0.004
35	0.039	0.041	0.021	0.001	0	0.006	0	0	0.002	0	0.003
36	0.036	0.035	0.017	0.001	0	0.004	0	0	0.001	0	0.002
37	0.034	0.031	0.014	0.001	0	0.003	0	0	0.001	0	0.001
38	0.031	0.026	0.011	0.001	0	0.002	0	0	0.001	0	0.001
39	0.029	0.023	0.009	0	0	0.002	0	0	0	0	0.001
40	0.027	0.019	0.007	0	0	0.001	0	0	0	0	0
41	0.024	0.016	0.006	0	0	0.001	0	0	0	0	0
42	0.022	0.013	0.005	0	0	0.001	0	0	0	0	0
43	0.019	0.011	0.004	0	0	0	0	0	0	0	0
44	0.018	0.009	0.003	0	0	0	0	0	0	0	0
45	0.016	0.007	0.002	0	0	0	0	0	0	0	0
46	0.014	0.006	0.002	0	0	0	0	0	0	0	0
47	0.012	0.005	0.001	0	0	0	0	0	0	0	0
48	0.011	0.004	0.001	0	0	0	0	0	0	0	0
49	0.01	0.003	0.001	0	0	0	0	0	0	0	0
Delay	Node *n* (Farm *f*)										
d	12	13	14	15	16	17	18	19	20	21	22
0	0	0	0	0.005	0.131	0	0	0	0	0	0
1	0	0	0	0.068	0.229	0	0	0	0	0	0
2	0	0	0	0.148	0.142	0	0.002	0	0	0	0
3	0	0	0.003	0.173	0.09	0	0.013	0	0	0	0.003
4	0	0	0.012	0.16	0.076	0	0.031	0	0	0.001	0.023
5	0	0	0.028	0.129	0.071	0	0.046	0	0.001	0.009	0.068
6	0	0.002	0.046	0.094	0.066	0	0.055	0	0.003	0.033	0.121
7	0	0.009	0.06	0.064	0.057	0.002	0.062	0.003	0.012	0.07	0.15
8	0.001	0.023	0.064	0.042	0.046	0.006	0.068	0.009	0.028	0.106	0.146
9	0.004	0.043	0.061	0.028	0.033	0.015	0.07	0.021	0.05	0.125	0.125
10	0.01	0.065	0.055	0.02	0.023	0.029	0.069	0.042	0.073	0.126	0.101
11	0.022	0.083	0.049	0.015	0.014	0.047	0.064	0.066	0.092	0.116	0.078
12	0.038	0.093	0.044	0.013	0.009	0.066	0.057	0.088	0.106	0.102	0.059
13	0.056	0.095	0.04	0.011	0.005	0.082	0.049	0.105	0.112	0.086	0.043
14	0.071	0.091	0.037	0.008	0.003	0.093	0.04	0.112	0.11	0.07	0.029
15	0.082	0.084	0.033	0.006	0.002	0.1	0.031	0.109	0.101	0.053	0.019
16	0.087	0.074	0.028	0.005	0.001	0.1	0.023	0.1	0.086	0.038	0.012
17	0.088	0.063	0.023	0.003	0.001	0.095	0.016	0.085	0.07	0.025	0.007
18	0.084	0.052	0.019	0.002	0	0.085	0.011	0.07	0.053	0.016	0.004
19	0.077	0.042	0.014	0.001	0	0.072	0.007	0.054	0.038	0.01	0.002
20	0.068	0.032	0.01	0.001	0	0.058	0.004	0.041	0.026	0.005	0.001
21	0.059	0.024	0.007	0.001	0	0.044	0.003	0.03	0.017	0.003	0.001
22	0.048	0.017	0.005	0	0	0.032	0.002	0.021	0.01	0.002	
23	0.039	0.012	0.003	0	0	0.023	0.001	0.015	0.006	0.001	
24	0.03	0.008	0.002	0	0	0.016	0.001	0.01	0.004	0	
25	0.023	0.005	0.001	0	0	0.01	0	0.007	0.002	0	
26	0.016	0.003	0.001	0	0	0.007	0	0.005	0.001	0	
27	0.012	0.002	0	0	0	0.004	0	0.003	0.001	0	
28	0.008	0.001	0	0	0	0.003	0	0.002	0	0	
29	0.005	0.001	0	0	0	0.002	0	0.001	0	0	
30	0.003	0	0	0	0	0.001	0	0.001	0	0	
31	0.002	0	0	0	0	0.001	0	0.001	0	0	

32	0.001	0	0	0	0	0	0	0	0	0	
33	0.001	0	0	0	0	0	0	0	0	0	
34	0.001	0	0	0	0	0	0	0	0	0	
Delay	Node *n* (Farm *f*)										
d	23	24	25	26	27	28	29	30	31	32	33
0	0.003	0	0	0	0.078	0	0	0	0	0	0
1	0.048	0	0	0	0.098	0	0	0	0	0.003	0.024
2	0.118	0	0	0.003	0.07	0	0	0.001	0.003	0.045	0.177
3	0.12	0	0	0.028	0.106	0	0.002	0.008	0.029	0.142	0.294
4	0.093	0	0.001	0.099	0.144	0.001	0.014	0.037	0.087	0.182	0.213
5	0.076	0.001	0.008	0.171	0.148	0.007	0.05	0.08	0.137	0.153	0.116
6	0.07	0.006	0.023	0.179	0.121	0.026	0.103	0.107	0.145	0.122	0.069
7	0.07	0.021	0.049	0.141	0.087	0.061	0.145	0.114	0.132	0.105	0.046
8	0.071	0.046	0.079	0.104	0.057	0.101	0.159	0.114	0.116	0.087	0.028
9	0.068	0.076	0.106	0.079	0.036	0.13	0.147	0.113	0.1	0.065	0.016
10	0.061	0.102	0.124	0.063	0.022	0.139	0.12	0.108	0.083	0.043	0.008
11	0.05	0.116	0.129	0.047	0.014	0.13	0.09	0.096	0.063	0.026	0.004
12	0.039	0.118	0.121	0.033	0.008	0.11	0.063	0.077	0.044	0.014	0.002
13	0.029	0.109	0.104	0.021	0.005	0.087	0.042	0.057	0.028	0.007	0.001
14	0.021	0.094	0.082	0.013	0.003	0.065	0.027	0.038	0.016	0.004	0.001
15	0.014	0.078	0.061	0.008	0.002	0.047	0.017	0.023	0.009	0.002	
16	0.009	0.062	0.042	0.005	0.001	0.033	0.01	0.013	0.004	0.001	
17	0.006	0.048	0.028	0.003	0.001	0.022	0.006	0.007	0.002	0	
18	0.004	0.036	0.017	0.002	0	0.015	0.003	0.004	0.001	0	
19	0.002	0.026	0.011	0.001	0	0.01	0.002	0.002	0	0	
20	0.001	0.019	0.006	0.001	0	0.006	0.001	0.001	0	0	
21	0.001	0.014	0.004	0	0	0.004	0	0	0	0	
22	0.001	0.009	0.002	0	0	0.002	0	0	0	0	
23	0	0.006	0.001	0	0	0.001	0	0	0	0	
24	0	0.004	0.001	0	0	0.001	0	0	0	0	
25	0	0.003	0	0	0	0.001	0	0	0	0	
26	0	0.002	0	0	0	0	0	0	0	0	
27	0	0.001	0	0	0	0	0	0	0	0	
28	0	0.001	0	0	0	0	0	0	0	0	
Delay	Node *n* (Farm *f*)										
d	34	35	36	37	38	39	40	41	42	43	44
0	0	0	0	0.002	0	0	0.022	0.182	0	0	0
1	0	0	0	0.115	0	0.008	0.294	0.448	0	0	0.003
2	0.005	0.005	0.001	0.372	0	0.045	0.379	0.161	0	0.005	0.046
3	0.038	0.044	0.005	0.288	0.005	0.091	0.17	0.07	0.002	0.06	0.164
4	0.101	0.132	0.019	0.115	0.027	0.136	0.071	0.057	0.014	0.19	0.247
5	0.151	0.193	0.043	0.048	0.076	0.172	0.036	0.04	0.042	0.271	0.231
6	0.166	0.189	0.076	0.027	0.136	0.177	0.017	0.022	0.08	0.229	0.158
7	0.152	0.15	0.115	0.015	0.176	0.148	0.007	0.01	0.114	0.138	0.087
8	0.122	0.108	0.145	0.008	0.178	0.103	0.002	0.005	0.13	0.066	0.04
9	0.09	0.072	0.154	0.004	0.148	0.062	0.001	0.002	0.129	0.027	0.016
10	0.063	0.046	0.141	0.002	0.107	0.033	0	0.001	0.115	0.01	0.006
11	0.041	0.028	0.111	0.001	0.068	0.016	0	0.001	0.095	0.004	0.002
12	0.027	0.016	0.079	0.001	0.039	0.007	0	0.001	0.075	0.001	0.001
13	0.017	0.009	0.051	0	0.021	0.003	0	0	0.057	0	0
14	0.01	0.005	0.03	0	0.01	0.001	0	0	0.041	0	0
15	0.006	0.002	0.016	0	0.005	0	0	0	0.03	0	0
16	0.004	0.001	0.008	0	0.002	0	0	0	0.021	0	0

17	0.002	0	0.004	0	0.001	0	0	0	0.015	0	0
18	0.001	0	0.002	0	0	0	0	0	0.011	0	0
19	0.001	0	0.001	0	0	0	0	0	0.008	0	0
20	0	0	0	0	0	0	0	0	0.006	0	0
21	0	0	0	0	0	0	0	0	0.004	0	0
22	0	0	0	0	0	0	0	0	0.003	0	0
23	0	0	0	0	0	0	0	0	0.002	0	0
24	0	0	0	0	0	0	0	0	0.002	0	0
25	0	0	0	0	0	0	0	0	0.001	0	0
26	0	0	0	0	0	0	0	0	0.001	0	0
27	0	0	0	0	0	0	0	0	0.001	0	0
28	0	0	0	0	0	0	0	0	0.001	0	0
Delay	Node n (Farm f)										
d	45	46	47	48	49	50	51	52	53	54	55
0	0.044	0	0	0	0.143	0	0	0.065	0	0	0.002
1	0.328	0	0.005	0.048	0.2	0	0	0.183	0	0.009	0.122
2	0.279	0.001	0.095	0.297	0.208	0.001	0.016	0.277	0.009	0.118	0.409
3	0.151	0.019	0.29	0.365	0.199	0.019	0.108	0.25	0.061	0.299	0.308
4	0.099	0.077	0.313	0.191	0.133	0.08	0.238	0.141	0.148	0.288	0.113
5	0.058	0.154	0.183	0.069	0.071	0.159	0.263	0.059	0.197	0.164	0.032
6	0.027	0.195	0.075	0.021	0.031	0.196	0.187	0.019	0.187	0.073	0.009
7	0.01	0.183	0.026	0.006	0.011	0.179	0.103	0.005	0.148	0.03	0.003
8	0.003	0.142	0.009	0.002	0.004	0.137	0.049	0.001	0.103	0.012	0.001
9	0.001	0.097	0.003	0	0.001	0.093	0.021	0	0.065	0.005	0
10	0	0.06	0.001	0	0	0.059	0.009	0	0.039	0.002	0
11	0	0.034	0	0	0	0.035	0.004	0	0.021	0.001	0
12	0	0.019	0	0	0	0.02	0.001	0	0.011	0	0
13	0	0.01	0	0	0	0.011	0.001	0	0.006	0	0
14	0	0.005	0	0	0	0.006	0	0	0.003	0	0
15	0	0.003	0	0	0	0.003	0	0	0.001	0	0
16	0	0.001	0	0	0	0.001	0	0	0.001	0	0
17	0	0.001	0	0	0	0.001	0	0	0	0	0
Delay	Node n (Farm f)										
d	56	57	58	59	60	61	62				
0	0.065	0	0	0.012	0.1	0.404	0.236				
1	0.427	0.035	0.045	0.206	0.525	0.573	0.502				
2	0.35	0.183	0.272	0.368	0.296	0.023	0.163				
3	0.122	0.271	0.342	0.23	0.062	0	0.06				
4	0.03	0.225	0.194	0.106	0.012	0	0.025				
5	0.006	0.143	0.085	0.047	0.003	0	0.01				
6	0.001	0.077	0.037	0.02	0.001	0	0.004				
7	0	0.038	0.015	0.008	0	0	0.001				
8	0	0.017	0.006	0.003	0	0	0				
9	0	0.007	0.002	0.001	0	0	0				
10	0	0.003	0.001	0	0	0	0				
11	0	0.001	0	0	0	0	0				

Table D.3: Response matrix for the river (r=1). All the coefficients not listed in the table are equal to zero.

Year (t)	Committed capacity C^{GW}_{1t} (kg)		Available capacity C^{0}_{1t} = Tradable capacity C_{1t} (kg) *	
	Sustainable	Intensive	Sustainable	Intensive
2011	114,267	194,491	6,380	-73,844 (0)
2012	105,310	178,875	15,337	-58,228 (0)
2013	93,119	158,112	27,528	-37,465 (0)
2014	80,440	137,642	40,207	-16,995 (0)
2015	68,897	119,439	51,750	1,208
2016	58,817	103,351	61,830	17,297
2017	49,968	88,689	70,679	31,958
2018	42,835	76,197	77,812	44,450
2019	36,986	65,586	83,662	55,061
2020	32,113	56,633	88,534	64,014
2021	28,055	49,140	92,592	71,507
2022	24,437	42,562	96,210	78,085
2023	21,391	37,037	99,256	83,610
2024	18,801	32,347	101,846	88,300
2025	16,447	28,143	104,200	92,504
2026	14,425	24,562	106,222	96,085
2027	12,637	21,382	108,010	99,265
2028	11,049	18,688	109,598	101,960
2029	9,661	16,273	110,986	104,374
2030	8,377	14,145	112,270	106,502
2031	7,262	12,250	113,385	108,397
2032	6,290	10,657	114,357	109,990
2033	5,399	9,166	115,248	111,481
2034	4,629	7,920	116,018	112,727
2035	3,952	6,804	116,695	113,843
2036	3,361	5,859	117,286	114,788
2037	2,853	5,033	117,794	115,614
2038	2,417	4,345	118,230	116,303
2039	1,988	3,651	118,659	116,996
2040	1,712	3,209	118,935	117,438
2041	1,391	2,688	119,256	117,959
2042	1,193	2,366	119,454	118,281
2043	967	1,985	119,680	118,662
2044	827	1,750	119,820	118,897
2045	669	1,472	119,978	119,175
2046	572	1,302	120,075	119,345
2047	464	1,097	120,184	119,550
2048	397	972	120,250	119,675
2049	323	776	120,324	119,872
2050	277	691	120,370	119,956
2051	232	598	120,415	120,049
2052	189	505	120,458	120,142

2053	164	451	120,483	120,196
2054	134	382	120,513	120,266
2055	117	342	120,530	120,305
2056	96	289	120,551	120,358
2057	84	259	120,563	120,388
2058	70	220	120,577	120,427
2059	61	198	120,586	120,449
T ≥ 2060	0	0	120,647	120,647

Table D.4: Tradable capacities for the two available capacity scenarios based on sustainable and intensive land uses.

*$C_{1t} = C^0{}_{1t} = (C^{SD}{}_1 - C^N{}_1) - C^{GW}{}_{1t}$ =120,647 – $C^{GW}{}_{1t}$.

Appendix E

AMPL MODELS, RESULTS AND CALCULATIONS

The appendix presents the AMPL formulations and the results based on the physical simulation model and information discussed in Appendix D. We used AMPL to model the LPs and MS Excel to analyse the results.

E.1 Optimal Loading Model (OLM)

This section is based on the generalized Optimal Loading Model (OLM) discussed in Chapter 7. Receptor capacities are based on sustainable prior land use (4th column in Table D.4).

E.1.1 OLM AMPL Formulation

```
param numFarms=62;
param numNodes=62;
param numReceptors=1;
param maxDelay=49;
param permitLimit=5;
param maxBids=5;
set F=1..numFarms by 1;
set N=1..numNodes by 1;
set R=1..numReceptors by 1;
set D=0..maxDelay by 1;
set S=1..permitLimit by 1;
set T=1..maxDelay+permitLimit by 1;
set K=1..maxBids by 1;

#~ Setting the bids
```

```
param bidType {f in F};
param farmArea {f in F};
param dairyBidQ {k in K};
param dairyBidP {k in K};
param sheepBidQ {k in K};
param sheepBidP {k in K};
param U {f in F,S,k in K} = farmArea[f]*(if bidType[f]=1 then dairyBidQ[k] else (if
        bidType[f]=2 then sheepBidQ[k] else 22));          #~Bid quantity
param P {f in F,S,k in K}= if bidType[f]=1 then dairyBidP[k] else (if bidType[f]=2
        then sheepBidP[k] else 28.45);                     #~Bid Price

param H {N,R,D};          #~Response coefficient
param C {R,T};            #~Receptor capacity

#~ Decision variables
var x {F,S,K}>=0;    #~Quantity accepted from each bid
var q {F,S};         #~Final quantity
var nodalQ {N,S};    #~Nodal loading

#~ Model:OLM
maximize benefit: sum {f in F} (sum {s in S}(sum {k in K}( x[f,s,k] * P[f,s,k])));
subject to uBound {f in F, s in S, k in K}: x[f,s,k] <= U[f,s,k];
subject to lBound {f in F, s in S, k in K}: x[f,s,k] >=0;
subject to farmPermit {f in F, s in S}: q[f,s] - sum{k in K} x[f,s,k] = 0;
subject to nodalLoad {n in N, s in S}: nodalQ[n,s] - q[n,s] = 0;  #~Assuming a
                                                                  distinct node for each
                                                                  farm
subject to CapCons{r in R, t in T}: sum {n in N} (sum {s in max(1,t-
        maxDelay)..min(t,permitLimit)}(H[n,r,t-s] * nodalQ[n,s])) <= C[r,t];
data OLM.dat;

solve;
option display_round 3;
display {f in F, s in S} q[f,s]/farmArea[f];
option display_round 2;
display nodalLoad.dual;
display CapCons.dual;
```

OLM Data File: OLM.dat

```
param: bidType farmArea:=
1    1    50
2    2    25
3    1    62.5
....
…
62   2    131.25;
```

```
param: dairyBidQ   dairyBidP      sheepBidQ    sheepBidP :=
1      13     41    9       70
2      8      33    3       48
3      20     25    3       30
4      19     21    8       18
5      30     18    19      6;

param: C:=

1,1     6380
1,2     15337
1,3     27528
…
…
1,54    120647;

param: H:=
1,1,0  0
1,1,1  0
1,1,2  0
…
…
41,1,0 0.182
41,1,1 0.448
41,1,2 0.161
…
…
62,1,49 0;
```

E.1.2 OLM Results

This section includes the results produced by the OLM.

Final Permit Positions q_{fs} (kg/ha/year)					
Farm f	Permit year s				
	2011	2012	2013	2014	2015
1	90	90	90	90	90
2	42	42	42	42	42
3	90	90	90	90	90
4	42	42	42	42	42
5	41	60	90	90	90
6	90	90	90	90	90
7	110	110	110	110	110
8	23	42	42	42	42
9	42	42	42	42	42
10	90	90	90	90	90
11	90	90	90	90	90
12	90	90	90	90	90
13	42	42	42	42	42

14	90	90	90	90	90
15	15	15	15	15	15
16	21	21	39.022	39.355	41
17	90	90	90	90	90
18	23	23	42	42	42
19	42	42	42	42	42
20	42	42	42	42	42
21	90	90	90	90	90
22	23	23	37.222	42	42
23	15	15	23	23	23
24	42	42	42	42	42
25	90	90	90	90	90
26	110	110	110	110	110
27	15	15	15	15	23
28	90	90	90	90	90
29	23	23	42	42	42
30	90	90	90	90	90
31	110	110	110	110	110
32	21	21	41	90	90
33	12	12	12	15	15
34	21	60	90	90	90
35	15	15	15	23	42
36	23	23	42	42	42
37	0	0	0	0	0
38	15	23	23	42	42
39	21	21	43.365	90	90
40	21	21	13	13	21
41	15	12	15	12	12
42	23	23	42	42	42
43	0	0	110	110	110
44	13	21	21	41	90
45	12	12	12	12	12
46	110	110	110	110	110
47	21	13	13	21	41
48	15	12	12	12	12
49	21	21	21	21	21
50	15	15	23	23	42
51	0	0	110	110	110
52	21	21	13	13	21
53	0	110	110	110	110
54	12	12	12	12	15
55	15	12	12	12	12
56	12	15	12	12	12
57	21	21	13.446	21	41
58	0	0	0	0	0
59	21	21	13	13	21
60	14.47	15	14.93	12	12
61	110	0	110	0	0
62	15	12	15	12	12

Table E.1: OLM results for trading scenario 1, final permit allocations to the farms.

Nodal loading prices β_{ns}					
Node n	Permit year s				
	2011	2012	2013	2014	2015
1	$0.00	$0.00	$0.00	$0.00	$0.00
2	$0.00	$0.00	$0.00	$0.00	$0.00
3	$0.00	$0.00	$0.00	$0.00	$0.00
4	$1.17	$0.43	$0.09	$0.00	$0.00
5	$23.65	$19.99	$15.20	$9.94	$4.88
6	$0.26	$0.09	$0.00	$0.00	$0.00
7	$3.56	$1.30	$0.35	$0.00	$0.00
8	$10.22	$5.89	$2.64	$0.79	$0.09
9	$0.00	$0.00	$0.00	$0.00	$0.00
10	$1.70	$0.83	$0.35	$0.09	$0.00
11	$0.00	$0.00	$0.00	$0.00	$0.00
12	$0.00	$0.00	$0.00	$0.00	$0.00
13	$0.78	$0.18	$0.00	$0.00	$0.00
14	$7.02	$4.64	$2.55	$1.04	$0.26
15	$28.55	$27.91	$26.70	$23.52	$18.30
16	$25.88	$27.40	$25.00	$25.00	$23.71
17	$0.17	$0.00	$0.00	$0.00	$0.00
18	$9.07	$6.75	$4.65	$2.76	$1.13
19	$0.26	$0.00	$0.00	$0.00	$0.00
20	$1.09	$0.26	$0.09	$0.00	$0.00
21	$6.49	$2.90	$0.79	$0.09	$0.00
22	$17.06	$11.60	$6.00	$2.01	$0.28
23	$21.15	$19.29	$17.94	$15.57	$12.70
24	$1.87	$0.53	$0.09	$0.00	$0.00
25	$4.64	$2.04	$0.70	$0.09	$0.00
26	$24.81	$21.22	$16.09	$8.66	$2.46
27	$28.17	$28.61	$24.99	$21.23	$16.72
28	$5.62	$2.30	$0.62	$0.09	$0.00
29	$15.41	$9.59	$4.42	$1.23	$0.18
30	$15.25	$11.28	$7.28	$3.25	$0.71
31	$21.97	$17.79	$13.24	$7.62	$2.53
32	$27.97	$25.71	$21.76	$17.83	$12.29
33	$30.48	$32.06	$31.37	$27.74	$26.17
34	$25.14	$20.64	$14.96	$8.91	$3.30
35	$28.30	$24.34	$18.82	$11.56	$3.84
36	$12.80	$7.67	$3.98	$1.69	$0.44
37	$29.59	$30.95	$34.57	$32.41	$30.18
38	$19.88	$13.16	$6.79	$2.35	$0.45
39	$29.82	$26.43	$21.00	$14.16	$8.20
40	$30.66	$29.56	$33.05	$35.87	$29.84
41	$27.91	$30.37	$29.03	$33.35	$34.74
42	$12.37	$7.62	$3.72	$1.22	$0.18
43	$33.59	$31.15	$26.23	$16.53	$5.25
44	$33.19	$32.77	$29.50	$23.44	$14.21
45	$31.06	$30.31	$31.91	$35.02	$30.74
46	$26.47	$21.15	$14.15	$6.69	$1.68
47	$32.60	$34.77	$33.44	$31.46	$24.99
48	$29.97	$33.12	$35.76	$32.67	$33.33
49	$27.48	$32.46	$32.31	$32.38	$31.92
50	$26.49	$21.38	$14.57	$6.95	$1.68
51	$33.45	$31.95	$28.29	$21.11	$9.34
52	$29.20	$32.01	$33.71	$33.88	$32.62
53	$29.43	$25.67	$20.14	$13.11	$5.29
54	$32.12	$34.37	$33.20	$30.63	$25.92
55	$29.49	$31.17	$35.69	$34.32	$32.21

56	\$30.11	\$28.96	\$31.68	\$36.73	\$33.91
57	\$31.56	\$32.96	\$33.00	\$29.46	\$24.80
58	\$30.25	\$33.09	\$35.01	\$31.59	\$31.24
59	\$30.46	\$30.61	\$34.05	\$34.92	\$30.18
60	\$30.00	\$28.55	\$30.00	\$36.87	\$34.97
61	\$22.20	\$31.42	\$26.55	\$31.73	\$42.85
62	\$26.35	\$30.46	\$28.92	\$34.01	\$38.46

Table E.2: OLM results for trading scenario 1, nodal prices.

Receptor capacity prices λ_{1t}	
Year t	Price λ_{1t}
2011	\$0.00
2012	\$37.65
2013	\$27.25
2014	\$25.70
2015	\$35.24
2016	\$49.93
2017	\$0.00
2018	\$84.20
2019	\$1.03
2020-2064	\$0.00

Table E.3: OLM results for trading scenario 1, receptor capacity prices.

E.2 Optimal Resource Allocation Model (ORAM)

This section is based on the Optimal Resource Allocation Model (ORAM) discussed in Chapter 8, and the set of available receptor capacities calculated based on sustainable land use until 2010 (4^{th} column of Table D.4). We assume that the regulator participates in the market as a bank, and the available receptor capacities are currently owned by the regulator.

E.2.1 ORAM AMPL Formulation

```
param numFarms=62;
param numNodes=62;
param numReceptors=1;
param maxDelay=49;
param permitLimit=5;
param maxBids=5;
param maxBbids=1;
set F=1..numFarms by 1;
set N=1..numNodes by 1;
set R=1..numReceptors by 1;
set D=0..maxDelay by 1;
set S=1..permitLimit by 1;
set T=1..maxDelay+permitLimit by 1;
set K=1..maxBids by 1;
```

```
set L=1..maxBbids by 1;

#~ Setting farm bids
param bidType {f in F};
param farmArea {f in F};
param dairyBidQ {k in K};
param dairyBidP {k in K};
param sheepBidQ {k in K};
param sheepBidP {k in K};
param U {f in F,S,k in K} = farmArea[f]*(if bidType[f]=1 then dairyBidQ[k] else (if
        bidType[f]=2 then sheepBidQ[k] else 22));          #~Bid quantity
param P {f in F,S,k in K}= if bidType[f]=1 then dairyBidP[k] else (if bidType[f]=2
        then sheepBidP[k] else 28.45);                     #~Bid Price

param H {N,R,D};            #~Response coefficient
param C {R,T};              #~Receptor capacity

#~ Setting regulator bids
param U_Regulator {r in R, t in T, l in L} = if l=1 then C[r,t] else 0;
param P_Regulator {r in R, t in T, l in L}= if t<=permitLimit then 1 else 25;

var x {F,S,K}>=0;                  #~Quantity accepted from each farm bid
var x_Regulator {R,T,L}>=0;        #~Quantity accepted from each regulator bid
var q {F,S};                       #~final quantity for the farms
var q_Regulator {R,T};             #~final quantity for the regulator
var nodalQ {N,S};                  #~nodal loading

maximize benefit: sum {f in F} (sum {s in S}(sum {k in K}( x[f,s,k] * P[f,s,k]))) +
sum{l in L}(sum {r in R} (sum {t in T} (x_Regulator[r,t,l]*P_Regulator[r,t,l])));

subject to uBound {f in F, s in S, k in K}: x[f,s,k] <= U[f,s,k];
subject to lBound {f in F, s in S, k in K}: x[f,s,k] >=0;
subject to uBound_Reg {r in R, t in T, l in L}: x_Regulator[r,t,l] <=
U_Regulator[r,t,l];
subject to lBound_Reg {r in R, t in T, l in L}: x_Regulator[r,t,l] >=0;

subject to farmPermit {f in F, s in S}: q[f,s] - sum{k in K} x[f,s,k] = 0;
subject to regulatorHeld {r in R, t in T}: q_Regulator[r,t] - sum{l in L}
        x_Regulator[r,t,l] = 0;
subject to nodalLoad {n in N, s in S}: nodalQ[n,s] - q[n,s] = 0;  #~Assuming a
                                                                   discrete node for
                                                                   each farm
subject to CapCons{r in R, t in T}: sum {n in N} (sum {s in max(1,t-
        maxDelay)..min(t,permitLimit)}(H[n,r,t-s] * nodalQ[n,s])) + q_Regulator [r,t]
        = C[r,t];
```

```
data Str_ORAM1.dat;
solve;
option display_round 3;
display {f in F, s in S} q[f,s]/farmArea[f];
display {r in R, t in T} q_Regulator [r,t];    #~Regulator's ex-post capacity position
display {r in R, t in T} C[r,t]-q_Regulator [r,t];     #~Total capacity allocation
option display_round 2;
display nodalLoad.dual;
display CapCons.dual;
display benefit;
```

E.2.2 ORAM Results

Final Permit Positions q_{fs} (kg/ha/year)					
Farm f	Permit year s				
	2011	2012	2013	2014	2015
1	41	41	41	41	41
2	15	15	15	15	15
3	21	21	21	21	21
4	15	15	15	15	15
5	21	21	21	21	21
6	41	41	41	41	41
7	110	110	110	110	110
8	15	15	15	15	15
9	15	15	15	15	15
10	90	90	90	90	90
11	41	41	41	41	41
12	41	41	41	41	41
13	15	15	15	15	15
14	90	90	90	90	90
15	15	15	15	15	15
16	21	21	21	21	21
17	41	41	41	41	41
18	15	15	15	15	15
19	15	15	15	15	15
20	15	15	15	15	15
21	21	41	41	41	41
22	15	15	15	15	15
23	15	15	15	15	15
24	15	15	15	15	15
25	21	41	41	41	41
26	110	110	110	110	110
27	15	15	15	15	15
28	21	41	41	41	41
29	15	15	15	15	15
30	21	21	21	21	41
31	110	110	110	110	110
32	21	21	21	21	21
33	15	15	15	15	15
34	21	21	21	41	41
35	15	15	15	15	15
36	15	15	15	15	15
37	0	98.09	0	64.819	110
38	15	15	15	15	15
39	21	21	21	21	21

40	21	21	21	21	21
41	15	15	15	15	15
42	15	15	15	15	15
43	110	110	110	110	110
44	21	21	21	21	21
45	12	15	15	15	15
46	110	110	110	110	110
47	21	21	21	21	21
48	15	15	15	15	15
49	21	21	21	21	21
50	15	15	15	15	15
51	59.834	110	110	110	110
52	21	21	21	21	21
53	110	110	110	110	110
54	15	15	15	15	15
55	15	15	15	15	15
56	12	15	15	15	15
57	21	21	21	21	21
58	42.323	0	0	110	110
59	21	21	21	21	21
60	12	15	15	15	15
61	110	0	110	0	0
62	15	13.624	15	15	12

Table E.4: ORAM results for trading scenario 2, final permit allocations to the farms.

Nodal loading prices β_{ns}					
Node *n*	Permit year *s*				
	2011	2012	2013	2014	2015
1	\$21.53	\$21.53	\$21.53	\$21.53	\$21.53
2	\$24.30	\$24.30	\$24.30	\$24.30	\$24.30
3	\$25.15	\$25.15	\$25.15	\$25.15	\$25.15
4	\$24.56	\$24.55	\$24.55	\$24.55	\$24.55
5	\$26.77	\$26.15	\$25.52	\$25.13	\$25.01
6	\$23.47	\$23.47	\$23.47	\$23.47	\$23.47
7	\$24.96	\$24.92	\$24.92	\$24.92	\$24.92
8	\$24.58	\$24.38	\$24.31	\$24.30	\$24.30
9	\$23.70	\$23.70	\$23.70	\$23.70	\$23.70
10	\$17.24	\$17.21	\$17.20	\$17.20	\$17.20
11	\$24.95	\$24.95	\$24.95	\$24.95	\$24.95
12	\$23.40	\$23.40	\$23.40	\$23.40	\$23.40
13	\$23.10	\$23.10	\$23.10	\$23.10	\$23.10
14	\$16.41	\$16.24	\$16.15	\$16.12	\$16.12
15	\$28.27	\$27.53	\$27.16	\$26.41	\$25.51
16	\$27.00	\$28.69	\$27.12	\$27.49	\$27.33
17	\$24.82	\$24.82	\$24.82	\$24.82	\$24.82
18	\$18.67	\$18.44	\$18.24	\$18.14	\$18.12
19	\$25.02	\$25.02	\$25.02	\$25.02	\$25.02
20	\$25.06	\$25.05	\$25.05	\$25.05	\$25.05
21	\$25.00	\$24.93	\$24.92	\$24.92	\$24.92
22	\$25.46	\$25.00	\$24.83	\$24.80	\$24.80
23	\$26.54	\$26.09	\$25.98	\$25.53	\$24.79
24	\$24.96	\$24.95	\$24.95	\$24.95	\$24.95
25	\$25.05	\$24.98	\$24.97	\$24.97	\$24.97
26	\$26.90	\$25.96	\$25.27	\$25.05	\$25.02
27	\$27.00	\$28.20	\$26.53	\$26.27	\$26.10
28	\$25.04	\$24.98	\$24.97	\$24.97	\$24.97
29	\$25.50	\$25.15	\$25.04	\$25.02	\$25.02

30	$25.83	$25.34	$25.07	$25.01	$25.00
31	$26.53	$25.81	$25.23	$25.00	$24.98
32	$27.55	$27.21	$26.37	$25.41	$25.05
33	$28.25	$28.49	$28.13	$26.53	$25.18
34	$26.69	$25.92	$25.26	$24.97	$24.92
35	$27.24	$26.27	$25.38	$25.04	$25.00
36	$25.47	$25.20	$25.07	$25.03	$25.02
37	$28.74	$28.45	$29.10	$28.45	$25.92
38	$25.72	$25.22	$25.02	$24.97	$24.97
39	$27.45	$26.68	$26.00	$25.45	$25.12
40	$30.66	$28.00	$28.92	$29.22	$27.50
41	$29.21	$29.35	$27.95	$28.63	$29.35
42	$25.41	$25.12	$25.02	$25.00	$25.00
43	$28.18	$26.83	$25.54	$25.07	$25.02
44	$28.52	$27.83	$26.56	$25.42	$25.05
45	$31.00	$28.13	$28.58	$28.62	$27.89
46	$26.65	$25.74	$25.19	$25.03	$25.03
47	$28.86	$28.99	$27.76	$25.81	$25.04
48	$28.44	$29.05	$29.23	$27.62	$25.38
49	$26.88	$30.09	$28.17	$28.05	$27.17
50	$26.68	$25.74	$25.16	$25.01	$25.00
51	$28.45	$27.42	$25.96	$25.13	$25.00
52	$28.54	$29.25	$28.77	$28.21	$26.75
53	$27.40	$26.48	$25.54	$25.08	$25.00
54	$28.74	$28.94	$27.96	$26.04	$25.10
55	$28.82	$28.68	$29.44	$28.81	$26.00
56	$31.42	$28.10	$29.02	$29.66	$28.81
57	$28.63	$28.56	$28.03	$26.65	$25.29
58	$28.45	$28.89	$28.94	$27.40	$25.35
59	$29.88	$28.37	$29.06	$28.84	$26.78
60	$31.93	$28.03	$28.69	$29.64	$29.69
61	$25.31	$31.86	$27.33	$28.85	$31.14
62	$28.48	$30.00	$28.11	$29.08	$30.01

Table E.5: ORAM results for trading scenario 2, nodal prices.

Receptor capacity prices λ_{1t}	
Year t	Price λ_{1t}
2011	$1.00
2012	$42.49
2013	$24.48
2014	$29.30
2015	$28.36
2016	$33.35
2017-64	$25.00

Table E.6: ORAM results for trading scenario 2, receptor capacity prices.

Farm f	Nitrate loading until 2010 (kg/ka/year)	Final permit allocations via trading From 2011 to 2015, q_{fs} (kg/ha/year)				
		2011	2012	2013	2014	2015
1	11.9	41	41	41	41	41
2	3.6	15	15	15	15	15
3	53.3	21	21	21	21	21
4	3.6	15	15	15	15	15
5	22.6	21	21	21	21	21
6	22.6	41	41	41	41	41

7	15.7	110	110	110	110	110
8	10.8	15	15	15	15	15
9	3.6	15	15	15	15	15
10	80	90	90	90	90	90
11	1.7	41	41	41	41	41
12	11.9	41	41	41	41	41
13	3.6	15	15	15	15	15
14	22.6	90	90	90	90	90
15	10.8	15	15	15	15	15
16	22.6	21	21	21	21	21
17	53.3	41	41	41	41	41
18	1.7	15	15	15	15	15
19	3.6	15	15	15	15	15
20	10.5	15	15	15	15	15
21	11.9	21	41	41	41	41
22	10.5	15	15	15	15	15
23	3.6	15	15	15	15	15
24	10.8	15	15	15	15	15
25	22.6	21	41	41	41	41
26	79.9	110	110	110	110	110
27	3.6	15	15	15	15	15
28	22.6	21	41	41	41	41
29	1.7	15	15	15	15	15
30	53.3	21	21	21	21	41
31	79.9	110	110	110	110	110
32	53.3	21	21	21	21	21
33	10.8	15	15	15	15	15
34	11.9	21	21	21	41	41
35	10.5	15	15	15	15	15
36	10.8	15	15	15	15	15
37	79.9	0	66.792	86.136	0	110
38	3.6	15	15	15	15	15
39	22.6	21	21	21	21	21
40	53.3	21	21	21	21	21
41	10.8	13.281	15	15	15	12
42	10.5	15	15	15	15	15
43	79.9	0	110	110	110	110
44	53.3	21	21	21	21	21
45	1.7	12	15	15	15	15
46	79.9	110	110	110	110	110
47	22.6	21	21	21	21	21
48	3.6	15	15	15	15	15
49	22.6	21	21	21	21	21
50	3.6	15	15	15	15	15
51	1.6	0	110	110	110	110
52	53.3	21	21	21	21	21
53	79.9	110	110	110	110	110
54	1.7	15	15	15	15	15
55	10.5	15	15	15	12	15
56	10.8	12	15	15	15	12
57	22.6	21	21	21	21	21
58	79.9	68.232	0	0	0	110
59	11.9	21	21	21	21	21
60	3.6	12	15	15	15	12
61	79.9	110	0	0	110	0
62	10.8	15	15	15	15	12

Table E.7: ORAM results for trading scenario 3, final allocations to the farms.

Nodal loading prices β_{ns}					
Node *n*	Permit year *s*				
	2011	2012	2013	2014	2015
1	$21.53	$21.53	$21.53	$21.53	$21.53
2	$24.30	$24.30	$24.30	$24.30	$24.30
3	$25.15	$25.15	$25.15	$25.15	$25.15
4	$24.56	$24.55	$24.55	$24.55	$24.55
5	$27.04	$26.46	$25.77	$25.22	$25.02
6	$23.47	$23.47	$23.47	$23.47	$23.47
7	$24.98	$24.92	$24.92	$24.92	$24.92
8	$24.71	$24.43	$24.31	$24.30	$24.30
9	$23.70	$23.70	$23.70	$23.70	$23.70
10	$17.25	$17.21	$17.20	$17.20	$17.20
11	$24.95	$24.95	$24.95	$24.95	$24.95
12	$23.40	$23.40	$23.40	$23.40	$23.40
13	$23.10	$23.10	$23.10	$23.10	$23.10
14	$16.51	$16.29	$16.17	$16.12	$16.12
15	$28.40	$27.72	$27.40	$26.84	$25.92
16	$27.43	$28.77	$27.33	$27.21	$27.72
17	$24.82	$24.82	$24.82	$24.82	$24.82
18	$18.77	$18.54	$18.31	$18.15	$18.12
19	$25.02	$25.02	$25.02	$25.02	$25.02
20	$25.06	$25.05	$25.05	$25.05	$25.05
21	$25.05	$24.94	$24.92	$24.92	$24.92
22	$25.73	$25.13	$24.85	$24.80	$24.80
23	$26.64	$26.18	$26.02	$25.92	$25.08
24	$24.96	$24.95	$24.95	$24.95	$24.95
25	$25.09	$24.99	$24.97	$24.97	$24.97
26	$27.34	$26.39	$25.43	$25.07	$25.02
27	$27.36	$28.50	$26.91	$26.34	$26.08
28	$25.07	$24.99	$24.97	$24.97	$24.97
29	$25.72	$25.22	$25.05	$25.02	$25.02
30	$26.08	$25.52	$25.11	$25.01	$25.00
31	$26.85	$26.16	$25.39	$25.02	$24.98
32	$27.66	$27.44	$26.95	$25.68	$25.07
33	$28.30	$28.29	$28.69	$27.50	$25.33
34	$27.02	$26.29	$25.47	$25.00	$24.92
35	$27.62	$26.80	$25.63	$25.07	$25.00
36	$25.62	$25.29	$25.09	$25.04	$25.02
37	$28.70	$28.45	$28.45	$29.94	$26.66
38	$26.02	$25.35	$25.05	$24.97	$24.97
39	$27.80	$27.03	$26.26	$25.68	$25.17
40	$30.70	$28.18	$28.38	$29.33	$29.27
41	$30.00	$28.94	$28.94	$26.87	$30.76
42	$25.58	$25.20	$25.03	$25.00	$25.00
43	$28.67	$27.61	$25.90	$25.10	$25.02
44	$28.70	$28.31	$27.27	$25.70	$25.07
45	$31.28	$28.03	$28.90	$27.90	$29.69
46	$27.11	$26.09	$25.30	$25.04	$25.03
47	$28.71	$29.10	$28.90	$26.40	$25.07
48	$28.41	$28.69	$29.36	$29.18	$25.69
49	$27.13	$30.12	$28.33	$28.52	$27.27
50	$27.15	$26.11	$25.28	$25.01	$25.00
51	$28.70	$28.16	$26.54	$25.24	$25.00
52	$28.64	$29.13	$28.86	$28.84	$27.40
53	$27.75	$26.99	$25.87	$25.13	$25.00

54	\$28.66	\$28.91	\$28.98	\$26.75	\$25.16
55	\$28.69	\$28.68	\$28.65	\$30.49	\$26.79
56	\$31.80	\$27.91	\$29.02	\$28.67	\$31.09
57	\$28.63	\$28.63	\$28.45	\$27.56	\$25.52
58	\$28.45	\$28.62	\$29.12	\$28.82	\$25.65
59	\$29.84	\$28.49	\$28.55	\$29.58	\$28.05
60	\$32.55	\$27.67	\$29.19	\$27.65	\$32.32
61	\$26.75	\$31.04	\$28.97	\$26.36	\$31.46
62	\$29.43	\$29.43	\$29.13	\$27.18	\$31.31

Table E.8: ORAM results for trading scenario 3, nodal prices.

Payments due from farms		Receptor capacity prices and allocations			Payments due to the regulator $\lambda_{1t}\times(C_{1t}-q^{bank}_{1t})$
Farm f	Total payment $\sum_s\beta_{ns}\times q_{fs}$	Year t	Price λ_{1t}	Total allocation $C_{1t}-q^{bank}_{1t}$	
1	\$220,682.50	2011	\$1.00	4418	\$4,418.28
2	\$45,562.50	2012	\$45.14	15337	\$692,312.18
3	\$165,046.88	2013	\$20.94	27528	\$576,436.32
4	\$195,648.75	2014	\$35.00	40207	\$1,407,245.00
5	\$407,956.50	2015	\$19.73	51750	\$1,021,027.50
6	\$571,347.81	2016	\$40.00	58547	\$2,341,867.72
7	\$1,542,667.50	2017	\$25.00	61571	\$1,539,277.35
8	\$68,653.13	2018	\$25.00	61437	\$1,535,936.98
9	\$66,656.25	2019	\$25.00	58379	\$1,459,465.90
10	\$1,307,036.25	2020	\$25.00	54073	\$1,351,815.43
11	\$287,704.69	2021	\$25.00	49163	\$1,229,079.35
12	\$419,737.50	2022	\$25.00	44432	\$1,110,795.93
13	\$292,359.38	2023	\$25.00	40223	\$1,005,569.93
14	\$411,125.63	2024	\$25.00	36232	\$905,807.60
15	\$677,141.25	2025	\$25.00	32242	\$806,056.53
16	\$1,908,151.88	2026	\$25.00	28195	\$704,862.80
17	\$318,006.25	2027	\$25.00	24364	\$609,104.23
18	\$60,302.81	2028	\$25.00	20875	\$521,867.83
19	\$117,281.25	2029	\$25.00	17833	\$445,821.73
20	\$117,431.25	2030	\$25.00	15259	\$381,472.65
21	\$288,359.38	2031	\$25.00	13076	\$326,904.38
22	\$211,460.63	2032	\$25.00	11263	\$281,580.15
23	\$632,970.00	2033	\$25.00	9688	\$242,201.25
24	\$105,266.25	2034	\$25.00	8319	\$207,972.03
25	\$462,279.00	2035	\$25.00	7122	\$178,045.00
26	\$533,156.25	2036	\$25.00	6079	\$151,983.75
27	\$481,614.38	2037	\$25.00	5159	\$128,978.90
28	\$260,008.31	2038	\$25.00	4381	\$109,527.18
29	\$200,860.31	2039	\$25.00	3696	\$92,408.28
30	\$138,299.00	2040	\$25.00	3126	\$78,150.93
31	\$794,475.00	2041	\$25.00	2639	\$65,962.80
32	\$226,590.00	2042	\$25.00	2225	\$55,614.23
33	\$142,425.94	2043	\$25.00	1864	\$46,595.93
34	\$555,165.00	2044	\$25.00	1585	\$39,630.63
35	\$97,590.00	2045	\$25.00	1338	\$33,451.88
36	\$82,726.88	2046	\$25.00	1141	\$28,531.55
37	\$273,127.56	2047	\$25.00	968	\$24,194.85
38	\$71,077.50	2048	\$25.00	830	\$20,749.23

39	$329,025.38	2049	$25.00	705	$17,614.05
40	$210,585.38	2050	$25.00	610	$15,246.40
41	$280,335.00	2051	$25.00	525	$13,116.25
42	$117,946.88	2052	$25.00	457	$11,427.80
43	$142,491.25	2053	$25.00	400	$9,993.75
44	$301,330.31	2054	$25.00	346	$8,653.43
45	$78,493.50	2055	$25.00	298	$7,460.48
46	$530,351.25	2056	$25.00	260	$6,498.43
47	$145,089.00	2057	$25.00	226	$5,639.23
48	$185,495.63	2058	$25.00	192	$4,798.75
49	$667,973.25	2059	$25.00	169	$4,224.70
50	$48,206.25	2060	$25.00	148	$3,692.83
51	$432,877.50	2061	$25.00	110	$2,741.58
52	$337,530.38	2062	$25.00	76	$1,902.20
53	$988,721.25	2063	$25.00	48	$1,207.50
54	$116,825.63	2064	$25.00	23	$573.45
55	$102,901.50	Total			$21,877,514.90
56	$178,384.50				
57	$491,837.06				
58	$267,901.90				
59	$455,206.50				
60	$396,429.94				
61	$36,513.13				
62	$276,054.19				
Total	$21,876,457.83				

Table E.9: ORAM results for trading scenario 3, receptor capacity prices and allocations, and financial flows.

Farm f	Nitrate loading until 2010 (kg/ka/year)	Final permit allocations via trading From 2011 to 2015, q_{fs} (kg/ha/year)				
		2011	2012	2013	2014	2015
1	11.9	41	41	41	41	41
2	3.6	15	15	15	15	15
3	53.3	42.64	31.98	21.32	21	21
4	3.6	15	15	15	15	15
5	22.6	21	21	21	21	21
6	22.6	41	41	41	41	41
7	15.7	110	110	110	110	110
8	10.8	15	15	15	15	15
9	3.6	15	15	15	15	15
10	80	90	90	90	90	90
11	1.7	41	41	41	41	41
12	11.9	41	41	41	41	41
13	3.6	15	15	15	15	15
14	22.6	90	90	90	90	90
15	10.8	12	15	15	15	15
16	22.6	21	17.567	21	21	21
17	53.3	42.64	41	41	41	41
18	1.7	15	15	15	15	15
19	3.6	15	15	15	15	15
20	10.5	15	15	15	15	15
21	11.9	21	41	41	41	41
22	10.5	15	15	15	15	15

23	3.6	15	15	15	15	15
24	10.8	15	15	15	15	15
25	22.6	21	41	41	41	41
26	79.9	110	110	110	110	110
27	3.6	15	12	15	15	15
28	22.6	21	41	41	41	41
29	1.7	15	15	15	15	15
30	53.3	42.64	31.98	21.32	21	41
31	79.9	110	110	110	110	110
32	53.3	42.64	31.98	21.32	21	21
33	10.8	12	15	15	15	15
34	11.9	21	21	21	41	41
35	10.5	15	15	15	15	15
36	10.8	15	15	15	15	15
37	79.9	63.92	47.94	31.96	15.98	110
38	3.6	15	15	15	15	15
39	22.6	21	21	21	21	21
40	53.3	42.64	31.98	21.32	21	21
41	10.8	12	12	12	15	12
42	10.5	15	15	15	15	15
43	79.9	63.92	110	110	110	110
44	53.3	42.64	31.98	21.32	21	21
45	1.7	12	12	12	15	15
46	79.9	110	110	110	110	110
47	22.6	21	21	21	21	21
48	3.6	12	12	12	15	15
49	22.6	21	13.56	21	21	21
50	3.6	15	15	15	15	15
51	1.6	1.28	0.96	110	110	110
52	53.3	42.64	31.98	21.32	21	21
53	79.9	63.92	110	110	110	110
54	1.7	12	12	15	15	15
55	10.5	12	12	12	12	15
56	10.8	12	12	12	12	12
57	22.6	21	21	21	21	21
58	79.9	63.92	47.94	31.96	15.98	110
59	11.9	13	18.164	21	21	21
60	3.6	12	12	12	14.787	12
61	79.9	110	47.94	31.96	110	0
62	10.8	13.457	12	12	15	12

Table E.10: ORAM results for trading scenario 4, final permit allocations to the farms.

Final Permit Positions q_{fs} (kg/ha/year)					
Farm f	Permit year s				
	2011	2012	2013	2014	2015
1	90	90	90	90	90
2	42	42	42	42	42
3	90	90	90	90	90
4	42	42	42	42	42
5	90	90	90	90	90
6	90	90	90	90	90
7	110	110	110	110	110
8	42	42	42	42	42
9	42	42	42	42	42
10	90	90	90	90	90
11	90	90	90	90	90
12	90	90	90	90	90

13	42	42	42	42	42
14	90	90	90	90	90
15	15	15	15	15	15
16	21	21	21	21	21
17	90	90	90	90	90
18	42	42	42	42	42
19	42	42	42	42	42
20	42	42	42	42	42
21	90	90	90	90	90
22	15	15	15	15	15
23	42	42	42	42	42
24	42	42	42	42	42
25	90	90	90	90	90
26	110	110	110	110	110
27	15	15	15	15	15
28	90	90	90	90	90
29	15	15	15	15	15
30	21	21	21	21	41
31	110	110	110	110	110
32	21	21	21	21	21
33	15	15	12	15	15
34	21	21	21	21	41
35	15	15	15	15	15
36	15	15	15	15	15
37	0	0	0	0	110
38	15	15	15	15	15
39	21	21	21	21	21
40	21	21	21	21	21
41	12	12	15	15	12
42	42	42	42	42	42
43	0	110	110	110	110
44	21	21	21	21	21
45	12	15	15	12	12
46	110	110	110	110	110
47	21	21	21	21	21
48	15	12	12	15	15
49	21	21	21	21	21
50	15	15	15	15	15
51	0	0	110	110	110
52	21	21	21	21	21
53	0	110	110	110	110
54	15	12	12	15	15
55	12	15	12	12	15
56	12	15	15	12	12
57	21	21	21	21	21
58	0	0	0	0	110
59	21	21	21	21	21
60	12	14.678	15	12	12
61	110	0	110	72.69	0
62	14.868	12	15	13.842	12

Table E.11: ORAM results for trading scenario 5, final permit allocation to the farms.

Receptor capacity prices and allocations		
Year t	Price λ_{1t}	Total allocation, $C_{1t}-q^{bank}_{1t}$ (kg)
2011	$1.00	4,408
2012	$44.13	15,337
2013	$29.17	27,528
2014	$26.61	40,207
2015	$29.28	51,750
2016	$40.00	61,424
2017-64	$25.00	

Table E.12: ORAM results for trading scenario 5, receptor capacity prices.

E.3 ORAM with Multiple Banks

This section is based on the Optimal Resource allocation Model (ORAM) discussed in Chapter 8, and available capacities calculated based on intensive land use prior to 2010 (5th column of Table D.4). The regulator who possesses the currently available capacities, and a third party who has the ability to remove nitrates from the receptor, participate in the market as resource banks to sell receptor capacities.

E.3.1 ORAM AMPL Formulation for Multiple Banks

The following AMPL model is formulated assuming that the resource banks submit a single bid (offer) with a single (reservation) price, for each receptor capacity constraint.

```
param numFarms=62;
param numNodes=62;
param numReceptors=1;
param maxDelay=49;
param permitLimit=5;
param maxBids=5;
param numBanks=2;

set F=1..numFarms by 1;
set N=1..numNodes by 1;
set R=1..numReceptors by 1;
set D=0..maxDelay by 1;
set S=1..permitLimit by 1;
set T=1..maxDelay+permitLimit by 1;
set K=1..maxBids by 1;
set B=1..numBanks by 1;
```

```
#~ Setting farm bids
param bidType {f in F};
param farmArea {f in F};
param dairyBidQ {k in K};
param dairyBidP {k in K};
param sheepBidQ {k in K};
param sheepBidP {k in K};
param U {f in F,S,k in K} = farmArea[f]*(if bidType[f]=1 then dairyBidQ[k] else (if
        bidType[f]=2 then sheepBidQ[k] else 22));          #~Bid quantity
param P {f in F,S,k in K}= if bidType[f]=1 then dairyBidP[k] else (if bidType[f]=2
        then sheepBidP[k] else 28.45);                      #~Bid Price

param H {N,R,D};            #~Response coefficient
param C {R,T};              #~Receptor capacity

#~ Setting bank bids
param U_Bank {b in B, r in R, t in T} = if b=1 then C[r,t] else (if t<=5 then 75000
else 0);
param P_Bank {b in B, r in R, t in T}= if b=1 then (if t<=permitLimit then 1 else 25)
else 30;

var x {F,S,K}>=0;                 #~Quantity accepted from each farm bid
var x_Bank {B,R,T}>=0;            #~Quantity accepted from each bank bid
var q {F,S};                      #~final quantity for the farms
var nodalQ {N,S};                 #~nodal loading

maximize benefit: sum {f in F} (sum {s in S}(sum {k in K}( x[f,s,k] * P[f,s,k]))) +
sum {b in B} (sum {r in R} (sum {t in T} (x_Bank[b,r,t]*P_Bank[b,r,t])));

subject to uBound {f in F, s in S, k in K}: x[f,s,k] <= U[f,s,k];
subject to lBound {f in F, s in S, k in K}: x[f,s,k] >=0;
subject to uBound_Reg {b in B, r in R, t in T}: x_Bank[b,r,t] <= U_Bank[b,r,t];
subject to lBound_Reg {b in B, r in R, t in T}: x_Bank[b,r,t] >=0;

subject to farmPermit {f in F, s in S}: q[f,s] - sum{k in K} x[f,s,k] = 0;
subject to nodalLoad {n in N, s in S}: nodalQ[n,s] - q[n,s] = 0;   #~Assuming one
                                                                    node for each farm
subject to CapCons{r in R, t in T}: sum {n in N} (sum {s in max(1,t-
        maxDelay)..min(t,permitLimit)}(H[n,r,t-s] * nodalQ[n,s])) + sum {b in B}
        (x_Bank [b,r,t]) = C[r,t] + if t<=5 then 75000 else 0;

data Str_ORAM4.dat;
solve;
option display_round 3;
display {f in F, s in S} q[f,s]/farmArea[f];
```

display {b in B, r in R, t in T} x_Bank [b,r,t];
option display_round 2;
display nodalLoad.dual;
display CapCons.dual;

E.3.2 ORAM with Multiple Banks Results

Final Permit Positions q_{fs} (kg/ha/year)					
Farm f	Permit year s				
	2011	2012	2013	2014	2015
1	41	41	41	41	41
2	15	15	15	15	15
3	21	21	21	21	21
4	15	15	15	15	15
5	13	13	21	21	21
6	41	41	41	41	41
7	110	110	110	110	110
8	15	15	15	15	15
9	15	15	15	15	15
10	90	90	90	90	90
11	41	41	41	41	41
12	41	41	41	41	41
13	15	15	15	15	15
14	60	90	90	90	90
15	12	12	12	12	12
16	13	13	13	0	0
17	41	41	41	41	41
18	15	15	15	15	15
19	15	15	15	15	15
20	15	15	15	15	15
21	21	21	41	41	41
22	12	15	15	15	15
23	12	12	12	12	15
24	15	15	15	15	15
25	21	21	41	41	41
26	0	0	110	110	110
27	12	12	12	12	12
28	21	21	41	41	41
29	12	15	15	15	15
30	13	21	21	21	21
31	0	0	110	110	110
32	0	0	13	21	21
33	12	9	9	12	15
34	0	13	21	21	41
35	12	12	15	15	15
36	15	15	15	15	15
37	0	0	0	0	0
38	12	15	15	15	15
39	0	13	13	21	21
40	13	13	0	0	0
41	12	12	12	12	0
42	15	15	15	15	15
43	0	0	0	110	110
44	0	0	0	21	21
45	12	12	12	9	9
46	0	0	110	110	110
47	0	0	0	13	21

48	12	9	9	9	12
49	13	0	0	0	0
50	12	12	15	15	15
51	0	0	0	110	110
52	13	0	0	0	0
53	0	0	0	110	110
54	12	9	9	12	15
55	12	12	9	2.925	12
56	12	12	12	9	0
57	0	0	0	0	21
58	0	0	0	0	0
59	13	13	0	0	0
60	12	12	12	9	0
61	0	0	0	0	0
62	12	12	12	12	0

Table E.13: ORAM results for trading scenario 6, final allocations to the farms.

Receptor capacity prices		Receptor capacity sales (kg)		
Year t	Price λ_{1t}	Regulator $C_{rt}-q^{bank}_{11t}$	Supplier $75000\text{-}q^{bank}_{21t}$	Total allocation
2011	\$30.00	0	2922	2922
2012	\$30.00	0	10114	10114
2013	\$30.00	0	16262	16262
2014	\$30.00	0	18832	18832
2015	\$30.00	1208	16675	17883
2016	\$133.57	17297	0	17297
2017-64	\$25.00			

Table E.14: ORAM results for trading scenario 6, capacity prices and allocations.

Farm f	Final permit position for 2011 q_{fs} (kg/ha/year)	Farm f	Final permit position for 2011 q_{fs} (kg/ha/year)
1	41	32	21
2	15	33	15
3	21	34	21
4	15	35	15
5	21	36	15
6	41	37	0
7	110	38	15
8	15	39	21
9	15	40	21
10	90	41	15
11	41	42	15
12	41	43	110
13	15	44	21
14	90	45	15
15	15	46	110
16	21	47	21
17	41	48	15
18	15	49	21
19	15	50	15
20	15	51	110
21	41	52	21

22	15	53	110
23	15	54	15
24	15	55	15
25	41	56	15
26	110	57	21
27	15	58	0
28	41	59	21
29	15	60	15
30	21	61	0
31	110	62	15

Table E.15: ORAM results for trading scenario 7, final permit positions for the farms.

Receptor capacity prices		Ex-post (unsold) capacity positions (kg)		Total allocation to the farms (kg)
Year t	Price λ_{1t}	Regulator q^{bank}_{11t}	Supplier q^{bank}_{21t}	
2011	\$30.00	0	70736	4264
2012	\$30.00	0	63938	11062
2013	\$30.00	0	63745	11255
2014	\$30.00	0	63637	11363
2015	\$30.00	0	63923	12285
2016-64	\$25.00			

Table E.16: ORAM results for trading scenario 7, capacity prices and allocations.

E.4 Initial Distribution of Permits

The results presented in this section were also produced from the ORAM, but in calculating the financial flows, we assume that the farms possess initial permit holdings, based on their prior land uses. The available capacities are based on sustainable prior land use (4th column of Table D.4).

Farm f	Total payment $\sum_s\beta_{ns}\times(q_{fs}-Q^*_{fs})$	Year t	Capacity price λ_{rt}	Regulator's final position q^{bank}_{1t}	Regulator's initial position Q^{Bank*}_{1t} (kg)	Regulator's revenue $\lambda_{rt}\times(Q^{Bank*}_{1t}-q^{bank}_{1t})$
1	\$158,552.30	2011	\$1.00	1962	2308	\$346.71
2	\$34,955.55	2012	\$45.14	0	953	\$43,026.55
3	-\$241,290.67	2013	\$20.94	0	583	\$12,198.39
4	\$150,101.72	2014	\$35.00	0	510	\$17,836.70
5	-\$17,911.23	2015	\$19.73	0	332	\$6,555.69
6	\$265,857.89	2016	\$40.00	3283	3918	\$25,395.32
7	\$1,329,092.20	2017	\$25.00	9108	14038	\$123,261.10
8	\$20,705.78	2018	\$25.00	16375	26263	\$247,213.98
9	\$51,138.68	2019	\$25.00	25283	38689	\$335,132.15
10	\$180,080.55	2020	\$25.00	34461	50104	\$391,054.43
11	\$276,133.35	2021	\$25.00	43429	60257	\$420,715.10

12	$301,566.04	2022	$25.00	51778	69100	$433,047.43
13	$224,298.11	2023	$25.00	59033	76307	$431,854.43
14	$310,984.56	2024	$25.00	65614	82232	$415,457.35
15	$204,225.80	2025	$25.00	71958	87329	$384,276.28
16	-$83,776.95	2026	$25.00	78027	91702	$341,869.55
17	-$82,999.63	2027	$25.00	83646	95474	$295,693.98
18	$53,673.52	2028	$25.00	88723	98765	$251,039.58
19	$89,978.18	2029	$25.00	93153	101590	$210,926.98
20	$37,695.43	2030	$25.00	97011	104091	$176,985.65
21	$198,360.05	2031	$25.00	100309	106256	$148,691.63
22	$67,878.86	2032	$25.00	103094	108114	$125,493.65
23	$485,614.58	2033	$25.00	105560	109788	$105,702.75
24	$31,748.30	2034	$25.00	107699	111244	$88,617.27
25	$188,275.92	2035	$25.00	109573	112511	$73,443.50
26	$157,508.90	2036	$25.00	111207	113621	$60,359.25
27	$369,494.55	2037	$25.00	112635	114596	$49,033.40
28	$105,906.24	2038	$25.00	113849	115428	$39,465.18
29	$178,779.07	2039	$25.00	114963	116220	$31,438.53
30	-$148,331.34	2040	$25.00	115809	116816	$25,173.17
31	$234,709.58	2041	$25.00	116617	117422	$20,108.05
32	-$331,263.79	2042	$25.00	117229	117875	$16,132.73
33	$42,955.66	2043	$25.00	117816	118338	$13,047.42
34	$332,327.39	2044	$25.00	118235	118669	$10,851.38
35	$31,326.39	2045	$25.00	118640	119008	$9,190.37
36	$24,950.43	2046	$25.00	118934	119257	$8,091.30
37	-$140,157.19	2047	$25.00	119216	119503	$7,157.85
38	$54,530.66	2048	$25.00	119420	119682	$6,541.22
39	-$14,445.78	2049	$25.00	119619	119858	$5,973.05
40	-$307,865.79	2050	$25.00	119760	119979	$5,472.65
41	$70,735.12	2051	$25.00	119890	120092	$5,042.75
42	$37,860.95	2052	$25.00	120001	120188	$4,670.05
43	$14,320.66	2053	$25.00	120083	120256	$4,320.50
44	-$440,530.57	2054	$25.00	120167	120323	$3,896.67
45	$69,477.59	2055	$25.00	120232	120372	$3,509.97
46	$156,680.22	2056	$25.00	120291	120419	$3,201.93
47	-$6,370.10	2057	$25.00	120337	120453	$2,896.98
48	$142,312.24	2058	$25.00	120385	120489	$2,606.50
49	-$29,327.21	2059	$25.00	120417	120513	$2,405.45
50	$36,983.84	2060	$25.00	120448	120535	$2,163.83
51	$425,099.65	2061	$25.00	120537	120602	$1,620.32
52	-$493,453.34	2062	$25.00	120571	120617	$1,157.45
53	$292,095.22	2063	$25.00	120599	120628	$727.75
54	$103,982.59	2064	$25.00	120624	120638	$341.95
55	$29,925.98	Total				$5,452,434
56	$42,271.14					

57	-$21,593.99
58	-$345,311.53
59	$204,994.66
60	$295,363.16
61	-$33,520.52
62	$74,647.85
Total	$5,452,007

Table E.17: ORAM results for scenario 8, receptor capacity prices and calculated fanatical flows. $Q^{Bank*}{}_{1t} = C_{1t} - \sum_f \sum_{s=\max(1,t-D)}^{\min(t,S)} H_{frt} Q^*{}_{fs}$.

E.5 Point and Nonpoint Source Trading

This section presents the results for point and nonpoint source trading, based on the ORAM. The available capacities are based on sustainable prior land use (4th column of Table D.4). To compare the allocations between point and nonpoint sources, the farm allocations are given in total kg/year rather than in kg/ha/year.

Final Permit Positions q_{fs} (kg/year)					
Farm f	Permit year s				
	2011	2012	2013	2014	2015
1	2050	2050	2050	2050	2050
2	375	375	375	375	375
3	1312	1312	1312	1312	1312
4	1594	1594	1594	1594	1594
5	3150	3150	3150	3150	3150
6	4869	4869	4869	4869	4869
7	12375	12375	12375	12375	12375
8	562	562	562	562	562
9	562	562	562	562	562
10	15188	15188	15188	15188	15188
11	2306	2306	2306	2306	2306
12	3588	3588	3588	3588	3588
13	2531	2531	2531	2531	2531
14	5062	5062	5062	5062	5062
15	4969	4969	4969	4969	4969
16	13781	13781	13781	13781	13781
17	2562	2562	2562	2562	2562
18	656	656	656	656	656
19	938	938	938	938	938
20	938	938	938	938	938
21	1312	2562	2562	2562	2562
22	1688	1688	1688	1688	1688
23	4875	4875	4875	4875	4875
24	844	844	844	844	844
25	2100	4100	4100	4100	4100
26	4125	4125	4125	4125	4125
27	3562	3562	3562	3562	3562
28	1181	2306	2306	2306	2306
29	1594	1594	1594	1594	1594

30	919	919	919	919	919
31	6188	6188	6188	6188	6188
32	1706	1706	1706	1706	1706
33	1031	1031	1031	1031	1031
34	3150	3150	3150	3150	6150
35	750	750	750	750	750
36	656	656	656	656	656
37	0	2505	3230	0	4125
38	562	562	562	562	562
39	2494	2494	2494	2494	2494
40	1444	1444	1444	1444	1444
41	1826	2062	2062	2062	1650
42	938	938	938	938	938
43	0	1375	1375	1375	1375
44	2231	2231	2231	2231	2231
45	450	562	562	562	562
46	4125	4125	4125	4125	4125
47	1050	1050	1050	1050	1050
48	1312	1312	1312	1312	1312
49	4725	4725	4725	4725	4725
50	375	375	375	375	375
51	0	4125	4125	4125	4125
52	2362	2362	2362	2362	2362
53	7562	7562	7562	7562	7562
54	844	844	844	844	844
55	750	750	750	600	750
56	1050	1312	1312	1312	1050
57	3544	3544	3544	3544	3544
58	3838	0	0	0	6188
59	3150	3150	3150	3150	3150
60	2325	2906	2906	2906	2325
61	688	0	0	688	0
62	1969	1969	1969	1969	1575
PS	1962	0	0	0	0

Table E.18: ORAM results for point and nonpoint source trading (scenario 9), final allocations.

Receptor capacity prices and allocations	
Year t	Price λ_{1t}
2011	\$5.00
2012	\$43.36
2013	\$21.43
2014	\$34.82
2015	\$19.78
2016	\$40.00
2017-64	\$25.00

Table E.19: ORAM results for point and nonpoint source trading (scenario 9), receptor capacity prices.

Final Permit Positions q_{fs} (kg/year)					
Farm f	Permit year s				
	2011	2012	2013	2014	2015
1	2050	2050	2050	2050	2050
2	375	375	375	375	375
3	1312	1312	1312	1312	1312
4	1594	1594	1594	1594	1594
5	3150	3150	3150	3150	3150
6	4869	4869	4869	4869	4869
7	12375	12375	12375	12375	12375
8	562	562	562	562	562
9	562	562	562	562	562
10	15188	15188	15188	15188	15188
11	2306	2306	2306	2306	2306
12	3588	3588	3588	3588	3588
13	2531	2531	2531	2531	2531
14	5062	5062	5062	5062	5062
15	3975	3975	4969	4969	4969
16	8531	8531	13781	13781	13781
17	2562	2562	2562	2562	2562
18	656	656	656	656	656
19	938	938	938	938	938
20	938	938	938	938	938
21	1312	2562	2562	2562	2562
22	1688	1688	1688	1688	1688
23	3900	4875	4875	4875	4875
24	844	844	844	844	844
25	2100	4100	4100	4100	4100
26	4125	4125	4125	4125	4125
27	2850	2850	3562	3562	3562
28	1181	2306	2306	2306	2306
29	1594	1594	1594	1594	1594
30	919	919	919	919	919
31	6188	6188	6188	6188	6188
32	1706	1706	1706	1706	1706
33	825	825	825	1031	1031
34	3150	3150	3150	3150	6150
35	750	750	750	750	750
36	656	656	656	656	656
37	0	0	0	0	4125
38	562	562	562	562	562
39	2494	2494	2494	2494	2494
40	894	894	1444	1444	1444
41	1650	1650	1650	1650	1650
42	938	938	938	938	938
43	0	1375	1375	1375	1375
44	2231	2231	2231	2231	2231
45	450	450	450	450	450
46	4125	4125	4125	4125	4125
47	650	1050	1050	1050	1050
48	1050	1050	1050	1312	1312
49	2925	2925	4432	4725	4725
50	375	375	375	375	375
51	0	0	4125	4125	4125
52	1462	1462	2362	2362	2362
53	0	7562	7562	7562	7562

54	675	675	675	844	844
55	600	600	600	600	750
56	1050	1050	1050	1050	1050
57	2194	3544	3544	3544	3544
58	0	0	0	0	6188
59	1950	1950	3150	3150	3150
60	2325	2325	2325	2325	2325
61	0	0	0	0	0
62	1575	1575	1575	1575	1575
PS	3458	4594	7764	10000	10106

Table E.20: ORAM results for point and nonpoint source trading (scenario 10), final allocations.

Receptor capacity prices and allocations	
Year t	Price λ_{1t}
2011	\$50.00
2012	\$50.00
2013	\$40.00
2014	\$34.03
2015	\$30.00
2016	\$40.00
2017-64	\$25.00

Table E.21: ORAM results for point and nonpoint source trading (scenario 10), receptor capacity prices.

Final Permit Positions for 2011 q_{fs} (kg/year)		
Farm f	PS and NPS trading	NPS trading
1	2050	2050
2	375	375
3	1312	1312
4	1594	1594
5	3150	3150
6	4869	4869
7	12375	12375
8	562	562
9	562	562
10	15188	15188
11	2306	2306
12	3588	3588
13	2531	2531
14	5062	5062
15	4969	4969
16	13781	22841
17	2562	2562
18	656	656
19	938	938
20	938	938
21	1312	1312
22	1688	1688
23	4875	4875
24	844	844
25	2100	2100
26	4125	4125

27	3562	3562
28	1181	1181
29	1594	1594
30	919	919
31	6188	6188
32	1706	1706
33	1031	1031
34	3150	3150
35	750	750
36	656	656
37	4125	4125
38	562	562
39	2494	2494
40	1444	1444
41	1650	2062
42	938	938
43	0	0
44	2231	2231
45	562	562
46	4125	4125
47	1050	1050
48	1312	1312
49	4725	9225
50	375	375
51	0	0
52	2362	2362
53	7562	7562
54	844	844
55	750	750
56	1312	1312
57	3544	3544
58	6188	6188
59	3150	3150
60	2906	2906
61	0	688
62	1575	1969
PS	2276	-

Table E.22: ORAM results for point and nonpoint source trading (scenario 11), final allocations.

E.6 Market Competitiveness

This section demonstrates the measures of market competitiveness discussed in Chapter 11 of the main thesis. We present the calculated values of the proposed measures based on the catchment example discussed in Appendix D.

Year	HHI^{M}_{Rt}	Year	HHI^{M}_{Rt}
2011	0.14	2036	0.11
2012	0.08	2037	0.12
2013	0.05	2038	0.14
2014	0.04	2039	0.15
2015	0.03	2040	0.17

2016	0.03	2041	0.19
2017	0.03	2042	0.21
2018	0.03	2043	0.23
2019	0.03	2044	0.25
2020	0.03	2045	0.26
2021	0.03	2046	0.29
2022	0.04	2047	0.31
2023	0.04	2048	0.32
2024	0.04	2049	0.33
2025	0.04	2050	0.36
2026	0.05	2051	0.39
2027	0.05	2052	0.39
2028	0.06	2053	0.40
2029	0.06	2054	0.43
2030	0.07	2055	0.46
2031	0.08	2056	0.49
2032	0.08	2057	0.49
2033	0.09	2058	0.52
2034	0.10	2059	0.54
2035	0.10	2060	0.56

Table E.23: Calculated values of HHI^{M}_{Rt}.

Contiguity index		
	S=1	S=5
Pair-wise CI		
1,2	0.92	0.92
17,19	0.95	0.96
8,42	0.94	0.95
46,50	0.99	1.00
35,53	0.97	0.98
CI for all 62 farms	0.33	0.39
CI for sets of farms		
1-10	0.49	0.52
1-20	0.48	0.51
21-30	0.64	0.67
31-40	0.53	0.60
41-50	0.41	0.50
46-55	0.44	0.55
50-62	0.37	0.49

Table E.24: Calculated values of the Contiguity Index (CI).